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Network of Energy Transfer on the Nanoscale and its Application to Solving Constraint Satisfaction Problems

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Abstract–This paper demonstrates that a network of optical energy transfer between quantum nanostructures mediated by optical near-field interactions, occurring at scales far below the wavelength of light, could be utilized for solving constraint satisfaction problems (CSPs). The optical energy transfer, from smaller quantum dots to larger ones, a quantum stochastic process, depends on the existence of resonant energy levels between the quantum dots or a state-filling effect occurring at the larger quantum dots. Such a spatial and temporal mechanism yields different evolutions of energy transfer patterns in multi-quantum-dots systems. We numerically demonstrate that optical energy transfer processes can solve a CSP. We consider such an approach pave the way for a novel computation paradigm beyond those of conventional optical or quantum computations.

1. Introduction

Novel computing devices and architectures are highly demanded to overcome the limitations of conventional ones that are based solely on electron transfer in terms of reducing power dissipation, solving computationally demanding problems, and so on. Also, nature-inspired architectures are attracting significant attention from various research arenas such computational neurosciences, stochastic-based computing and noise-based logic, and spatio-temporal computation dynamics [1].

Among these research, Aono et al. demonstrated the "amoeba-based computing", such as solving constraint satisfaction problem (CSP) [1], the traveling salesman problem (TSP), by utilizing the spatio-temporal oscillatory dynamics of the photoresponsive amoeboid organism Physarum combined with external optical feedback control. These demonstrations indicate that we can utilize inherent spatial and temporal dynamics for novel computing architectures and applications; such arguments should be applicable for nanometer-scale light and matter interactions [2]. In particular, energy transfer between quantum nanostructures mediated by optical near-field interactions plays a crucial role; its theoretical foundation has been given in the dressed photon model [3] and experimentally demonstrated in various quantum nanostructures [4-6] including room temperature operations [6]. Besides, the optical energy transfer has been shown to be 10^4-times more energy efficient than that of a bit-flip energy required in conventional electrically wired devices [7].

This paper theoretically demonstrates that optical energy transfer between quantum dots mediated by optical near-field interactions is utilized for solving a CSP. The optical energy transfer depends on the existence of resonant energy levels between the quantum dots (QDs) or the state filling effect occurring at the destination QDs. Also, as indicated by the quantum master equations, the energy transfer process is fundamentally probabilistic. Such a spatial and temporal mechanism yields different evolutions of energy transfer patterns combined with certain feedback mechanisms. In contrast to biological substrates, optical energy transfer is implemented by highly-controlled engineering means for designated structures. The operating speed of such optical-near-field mediated QD systems, which is in order of nanosecond when we concern with radiative relaxation processes, is also significantly faster than the ones based on biological organisms, which is in orders of seconds or minutes [1]. In addition, we should emphasize that the concept and the principles discussed in this paper is fundamentally different from those of conventional optical computing or optical signal processing which are limited by the abilities of propagating light. The concept and the principles are also different from quantum computing paradigm where superposition of all possible states is exploited so that it leads to a collect solution. The optical near-field-mediated energy transfer is a coherent process, indicating that an optical excitation could be transferred to all possible destination QDs via a resonant energy level, but such coherent interaction between QDs results in an unidirectional energy transfer by an energy dissipation process occurring in the larger dot. Thus, our approach paves another computation paradigm where both coherent and dissipative processes are exploited.

2. State-dependent Optical Energy Transfer via Near-Field Interactions for Solving a Constraint Satisfaction Problem (CSP)

Here we assume two spherical quantum dots whose radii are R_S and R_L, which we call QD_S and QD_{L1}, respectively, as shown in Fig. 1(a). There exists a resonance between the level of quantum number (1,0) of QD_S, denoted by S in Fig. 1(a), and that of quantum number (1,1) of QD_{L1}, marked by $L_1^{(U)}$. Note that the (1,1)-level of QD_{L1} is a dipole-forbidden energy level. However, optical near-fields allow this level to be populated by excitation. Therefore, an exciton in the (1,0)-level in QD_S could be transferred to the (1,1)-level in QD_{L1}. In QD_{L1}, due to the sublevel energy relaxation with a relaxation constant Γ, which is faster than the near-field interaction, the exciton relaxes to the (1,0)-level, denoted by $L_1^{(L)}$, from where it radiatively decays. Therefore, we find uni-directional optical excitation transfer from QD_S to QD_{L1}.

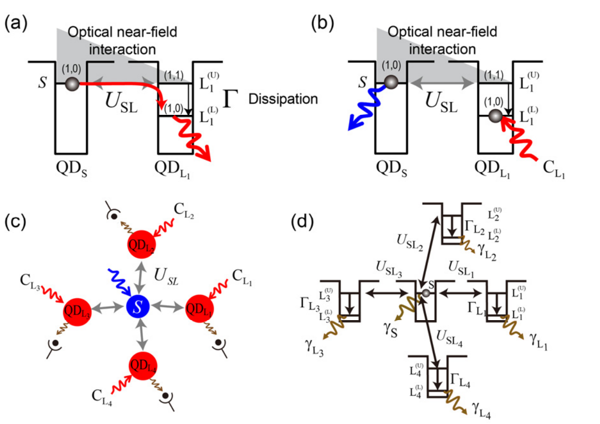

Fig. 1 (a,b) Optical energy transfer between QD mediated by near-field interaction. (c,d) Architecture of optical-energy-transfer-based problem solver studied in this paper.

When the lower energy level of the destination quantum dot is filled with another excitation (called "state filling"), an optical excitation occurring in a smaller QD cannot move to a larger one. This suggests two different patterns of optical energy transfer appear depending on occupation of the destination quantum dots (Fig. 1(b)).

Toward solving a constraint satisfaction problem (CSP) using optical energy transfer, we design an architecture where a smaller QD are surrounded by multiple larger QDs. In this paper, we assume four larger QDs each of which is labeled with QD_{L1}, QD_{L2}, QD_{L3}, QD_{L4} as indicated in Fig. 1(c). Fig. 1(d) shows representative parameterizations associated with the system. The (1,0)-level in QD_S is denoted by S, and the (1,1)-level in QD_{Li} is denoted by $L_i^{(U)}$. These levels are resonant with each other and are connected by inter-dot interactions denoted by U_{SLi} (i=1,...,4). The lower level in QD_{Li}, namely the (1,0)-level, is denoted by $L_i^{(L)}$, which could be filled via the sublevel relaxation denoted by Γ_{Li} from $L_i^{(U)}$. The radiations from the S and L_i levels are respectively represented by the relaxation constants γ_S and γ_{Li}. We call the inverse of those relaxation constants the radiation lifetime in the following. We also assume that the photon radiated from the lower level of QD_{Li} can be separately captured by photodetectors. In addition, we assume control lights, denoted by C_{Li} in Fig. 1(c), so that they could induce state filling effect at $L_i^{(L)}$. Summing up, Fig. 1(c) and (d) schematically represent the architecture of the system to be studied in this paper for solving a CSP.

First, we suppose that the system initially has one exciton in S. From the initial state, through the inter-dot interactions U_{SLi}, the exciton in S could be transferred to $L_i^{(U)}$ (i=1,...,4). Correspondingly, we can derive quantum master equations in the density matrix formalism [8]. The Liouville equation for the system is then given by

$$\frac{d\rho(t)}{dt} = -\frac{i}{\hbar}[H_{\rm int}, \rho(t)] - N_\Gamma \rho(t) - \rho(t) N_\Gamma \quad (1)$$

where $\rho(t)$ is the density matrix with respect to the five energy levels, $H_{\rm int}$ is interaction Hamiltonian, and N_Γ indicates relaxations. In the numerical calculation, we assume U_{SLi}^{-1}=100 ps, Γ_i^{-1}=10 ps, γ_{Li}^{-1}=1 ns and γ_S^{-1}~2.92 ns as a typical parameter set [8].

Based on the above modeling and parameterizations, we can calculate populations involving $L_1^{(L)}$, $L_2^{(L)}$, $L_3^{(L)}$, and $L_4^{(L)}$ which are relevant to the radiation from the larger QDs. Also, when QD_{Li} suffers from state filling by control lights C_{Li}, the energy transfer from the QD_S to QD_{Li} behaves differently.

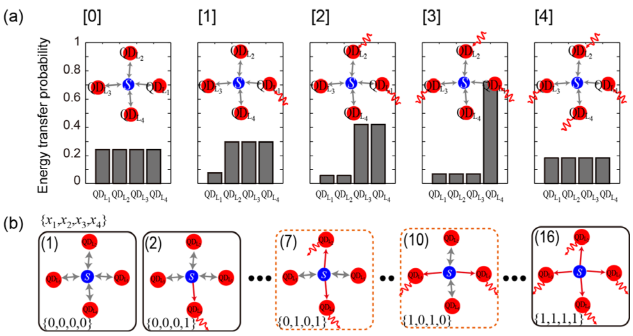

Fig. 2 (a) Estimated energy transfer probability depending on the control light beam(s). (b) Schematic representation of possible states of the system. States (7) and (10) correspond to the correct solutions.

We assume that the energy transfer probability to QD_{Li} is correlated with the integral of the populations with respect to $L_i^{(L)}$ as summarized in Fig. 2(a). We should notice that such integral of populations are indeed a figure-of-merit (FoM) indicating the trend of optical energy transfer from smaller one to the four larger dots; it does *not* hold the conservation law of the probability, namely, the summation of the transition probability to QD_{Li} is not unity. Instead, we see that the energy transfer to QD_{Li} occurs if a random number generated uniformly between 0 and 1 is less than the transition probability to QD_{Li} shown in Fig. 2(a); for example in the case of Fig. 2(a,[3]), the energy transfer to QD_{L4} is highly likely induced whereas the transfer to QD_{L1}, QD_{L2}, and QD_{L3} are less likely induced.

The idea for the problem solving is to control optical energy transfer by controlling the destination QD by control lights in an adequate feedback mechanisms. We assume that a photon radiation, or observation, from the energy level $L_i^{(L)}$ is equivalent that a binary value x_i results in a logical 1 level, while no observation of photon means $x_i=0$.

3. Application to Solving a Constraint Satisfaction Problem

We consider the following constraint satisfaction problem as an example regarding an array of N binary-valued variables x_i (i=1,...,N). The constraint is that $x_i=\mathrm{NOR}(x_{i-1},x_{i+1})$ should be satisfied for all i. That is, variable x_i should be consistent with a logical NOR operation of the two neighbors. For i=0 and N, the constraints are respectively given by $x_1=\mathrm{NOR}(x_N,x_2)$ and $x_N=\mathrm{NOR}(x_{N-1},x_1)$. We call this problem the "NOR problem" hereafter in this paper. Taking account of the nature of an individual NOR logic operation, one important inherent character is that if $x_i=1$ then its two neighbors should be both zero $x_{i-1}=x_{i+1}=0$. Recall that a photon radiated, or observed, from the energy level $L_i^{(L)}$ corresponds to a binary value $x_i=1$, whereas the absence of an observed photo means $x_i=0$. Therefore, $x_i=1$ should mean that the optical energy transfer to both $L_{i-1}^{(L)}$ and $L_{i+1}^{(L)}$ is prohibited so that $x_{i-1}=x_{i+1}=0$ is satisfied. Therefore, the feedback or control mechanism is that;

[Control mechanism] If $x_i=1$ at cycle t, then the control light beams C_{i-1} and C_{i+1} are turned on at cycle $t=t+1$.

In the case of N=4, there are in total 2^4 optical energy transfer patterns from the smaller dot to larger ones. In this case, the variables satisfying the constraints do exist, and they are given by $\{x_1, x_2, x_3, x_4\}=\{0,1,0,1\}$ and {1,0,1,0}, which we call "correct solutions". Fig. 2(b) schematically represent some of the possible states where the state (7) and (10) respectively corresponding to the correct solutions.

There are a few remarks regarding the NOR problem. One is about the potential deadlock, analogous to Dijkstra's "dining philosophers problem", as already argued by Aono et al. in Ref. [1]. Starting with an initial state $x_i=0$ for all i, and assuming a situation where optical energy is transferred to all larger QDs, we observe photon radiation from all energy levels $L_i^{(L)}$, namely, $x_i=1$ for all i. Then, based on the feedback mechanism shown above, all control light beams are turned on. If such a feedback mechanism perfectly inhibits the optical energy transfer from the smaller QD to the large ones at the next step t+1, the variables then go to $x_i=0$ for all i. This leads to all control light beams being turned off at t+2. In this manner, all variables constantly repeat a periodic switching between $x_i=0$ and $x_i=1$ in a synchronized manner. Consequently, the system can never reach the correct solutions. However, as indicated in Fig. 2(a), the probability of optical energy transfer to larger dots is in fact not zero even when all larger QDs are illuminated by control lights as shown in Fig. 2(a,[4]). Also, even for a non-illuminated destination QD, the energy transfer probability may not be exactly unity. Such a stochastic behavior of the optical energy transfer is a key role in solving the NOR problem. This nature is similar to the demonstrations in the amoeba-based computer [1] where fluctuations of chaotic oscillatory behavior involving spontaneous symmetry breaking in the amoeboid organism guarantees such a critical property.

The operating dynamics cause one pattern to change to another one in every iteration cycle. Thanks to the stochastic nature, each trial could exhibit a different evolution of the energy transfer patterns. In particular, the transition probability, shown in Fig. 2(a), affects the behavior of the transitions. Therefore, we introduce a gain factor (G) to be multiplied by the energy transfer probability summarized in Fig. 2(a).

The curves in Fig. 3(a) represent the evolution of the output appearance from QD_{Li}, namely, the ratio of the incidence when $x_i=1$ among 1,000 trials evaluated at each cycle. The curves in Fig. 3(b) characterizes the ratio of the appearance of the state that corresponding to the correct solutions; {0,1,0,1} (state 7) and {1,0,1,0} (state 10), respectively. When we closely examine the evolutions of x_i in Fig. 3(a), we can see that the pair x_1 and x_3 exhibit similar behavior and as do the pair x_2 and x_4. Also, the former pair exhibit larger values the latter pair show smaller values, and vice versa. This corresponds to the fact that correct solutions are likely to be induced as the iteration cycle increases.

Such a tendency is more clearly represented when we evaluate the time-averages of the characteristics in Fig. 3(a) and (b). Fig. 3(c) shows the evolutions of the ratio of the incidences when $x_i=1$, and Fig. 3(d) shows the ratios of State (7) and State (10) averaged over every 5 cycles. We can clearly observe a similar tendency to the one described above. Also, we should emphasize that, thanks to the probabilistic nature of the system, the states of correct solutions appear in an interchangeable manner. This is a clear indication of the fact that the probabilistic nature of the system autonomously seeks the solutions that satisfy the constraints of the NOR problem; the state-dependent probability of energy transfer plays the critical role in this. In other words, it should be emphasized that a non-local correlation is manifested in the evolution of x_i; for instance, when the system is in State (7), {0,1,0,1}, the probabilities of energy transfer to QD_{L1} and QD_{L3} are equally comparably low (due to state filling), whereas those to QD_{L2} and QD_{L4} are equally comparably high, indicating that the probability of the energy transfer to an individual QD_{Li} has inherent spatial patterns or non-local correlations. At the same time, the energy transfer to each QD_{Li} is indeed probabilistic; therefore, the energy transfer probability to, for instance, QD_{L1} is not zero even in the State (7), and thus, the state could transition from State (7) to State (10), and vice versa. In fact, starting with the initial condition of State (7), the ratio of output appearance from QD_{L1} and the ratio of the correct solutions evolve as shown in Fig. 3(e) and (f) where States (7) and (10) occur equally in the steady state around time cycles around 20.

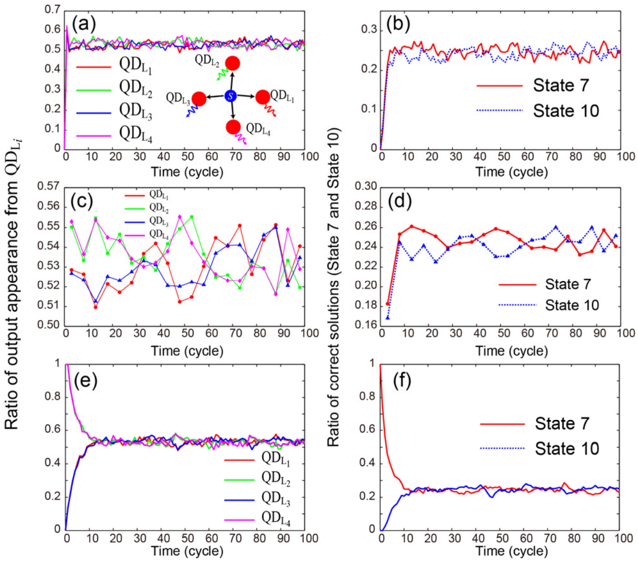

Fig. 3 (a) The evolution of the ratio of the output appearance from QD_{Li}, and (b) the ratio of the state corresponding to correct solutions. (c,d) Time-averaged traces (b) and (c), respectively. (e) The evolution of the ratio of the output appearance from QD_{Li}, and (f) the ratio of the state corresponding to correct solutions with the initial state (7).

Fig. 4 evaluates the accuracy rate, which is the number of correct solutions among 1000 different trials at t =100, as a function of the gain factor. We can see that gain of 2.5 provides the highest accuracy rate.

4. Conclusion

In summary, we have demonstrated that energy transfer between quantum nanostructures based on optical near-field interactions occurring at scales far below the wavelength of light has the potential to solve a constraint satisfaction problem. The optical energy transfer from smaller quantum dots to larger ones, which is a quantum stochastic process, depends on the existence of resonant energy levels between the quantum dots or a state-filling effect occurring at the destination quantum dots. We exploit these unique spatiotemporal mechanism in optical energy transfer to solve a constraint satisfaction problem, and numerically demonstrated that the NOR problem is successfully solved.

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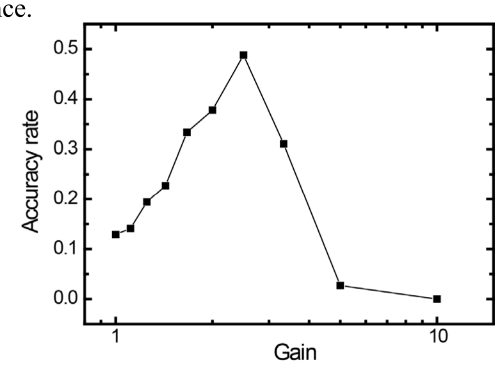

Fig. 4 Calculated accuracy rate, or the ratio of the number of correct states among all trials. The accuracy rate is maximized when the gain factor is 2.5.

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