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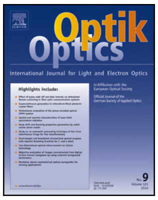

# Design of two-input nanophotonic AND/OR gate

Kian Aboutorabi, Saeed Golmohammadi*

*School of Engineering-Emerging Technologies, University of Tabriz, Tabriz 5166614761, Iran*

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ABSTRACT

In this paper, we report the dynamic behavior of two-input nanophotonic gate that works as an AND/OR gate at finite temperatures. Occupation levels of the proposed nanophotonic gate in the ON and OFF states under different values of temperature have been calculated. It is shown that when the gate operates as an AND gate, the output level occupation probability of the gate in the OFF (ON) state increases (decreases) with temperature. Hence, the ON/OFF ratio of the gate reduces with temperature. Also, it is shown that the output level occupation probabilities for the OR gate in the ON state decrease with temperature. As the output level occupation probabilities for this OR gate in either OFF state is equal to zero, the ON/OFF ratio for this gate is infinity.

## 1. Introduction

One of the most important properties that has made the optical near-field so much attractive during the past decade is the ability to transcend the light diffraction limit. Besides, optical near-field interaction between adjacent quantum dots with barriers larger than 4 eV, in which the exciton Bohr radius is much smaller than QDs dimensions, also makes it interesting for the studies on nanophotonic devices which in turn are the best candidate as the key block for all-optical nanometric devices with dimensions smaller than the diffraction limit of light [1]. Recently, qualitative innovations with novel performance have been established based on the distinctive properties of the optical near-field. The primitive nanophotonic devices that have been designed, were basic nanophotonic AND and NOT gates which make the basic blocks of the all-optical devices [2]. These nanophotonic gates are constituted of CuCl quantum dots of different size aligned on NaCl matrix with size smaller than the diffraction limit of light [3] which utilizes the optical near-fields to transfer energy between quantum dots in a way to do a logical operation between input fare-field signals and then generate a dispersive wave as their output [2]. On the downside, these gates do not have a good performance at room temperature. In order to overcome this problem new structures have been used which could guarantee the performance of the gate in the temperatures close to the room temperature [4].

One of the initial nanophotonic gates that have been reported is a three-QD AND gate with the configuration shown in Fig. 1 (Gate A) have developed by Ohtsu [4,5]. In order to simulate the device operation, Ohtsu have used the Born–Markov approximation and density matrix formulation for a two-CuCl-QD nanophotonic system coupled to a heat bath [4,5]. Besides, he has employed the rate equations to develop an appropriate numerical model in order to describe the switching behavior of three-CuCl-QD nanophotonic systems for near-zero temperatures [5].

In this work, we have proposed a modified nanophotonic AND/OR gate with configuration illustrated in Fig. 2 (Gate B). As can be seen in Figs. 1 and 2, the energy transfer path between input and output QDs of Gate A, unlike that for Gate B, is indirect. This modification has increased the gates ON/OFF ratio and it has also made possible that gate B to work at higher temperatures. In developing the latter numerical models, however, the optical near-field energy transfer rate was modeled by the Yukawa function. For this reason, these models, unlike the one based on density matrix formulation, are not suitable for finite temperatures. To overcome this deficiency, a new set of coupled rate equations has developed which is much simpler than the density matrix formulation and yet capable of describing the operation of any multiple-dot nanophotonic system at finite temperatures [6].

Utilizing the numerical model developed in [6], we examine the operation of both three-QD nanophotonic AND gates of Figs. 1 and 2(a) and nanophotonic OR gate of Fig. 2(b), at various finite temperatures. In this investigation, we have shown that at elevated temperatures, there are two nontrivial OFF states that exist for either nanophotonic switching AND gates of Figs. 1 and 2(a). In addition, It is indicated that there is only one trivial OFF state for the nanophotonic OR gate of Fig. 2(b).

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* Corresponding author.
*E-mail addresses:* k.aboutorabi89@ms.tabrizu.ac.ir (K. Aboutorabi), sgolmohammadi@tabrizu.ac.ir (S. Golmohammadi).

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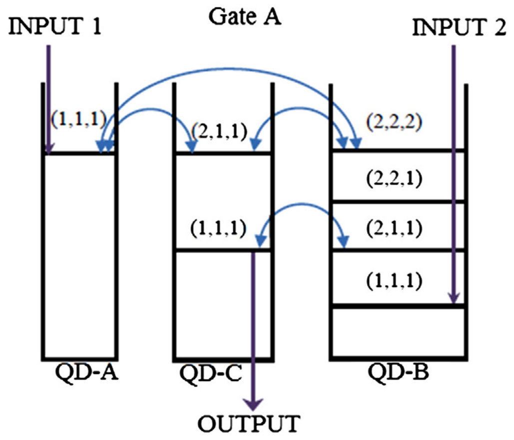

**Fig. 1.** Ohtsu's nanophotonic AND gate [4,5].

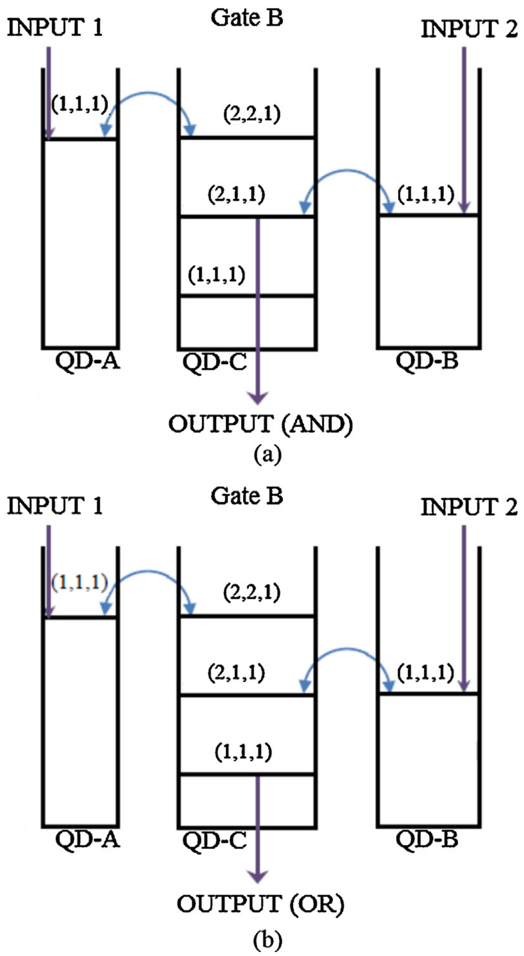

**Fig. 2.** New nanophotonic AND/OR gate: (a) AND operation pattern (b) OR operation pattern.

The rest of this paper is organized as follows: a brief overview of the AND/OR gate operating principle at finite temperatures is given in Section 2. In Section 3, the employed model for our numerical calculations is outlined. Section 4, reviews the results and discusses them. And finally, we close this paper by summarizing the main points discussed in this paper in Section 5.

## 2. Principles of operation at finite temperatures

In this section, we review the operating principles of the two-input nanophotonic AND gates of Figs. 1 and 2(a) and nanophotonic OR gate of Fig. 2(b) at finite temperatures; assuming each gate to be made of cubic CuCl-QDs in a NaCl matrix. The operation of each of these nanophotonic gates is based on the optical near-field energy transfer between the adjacent QDs and the intra-dot transitions by coupling to a phonon heat bath that exists in the NaCl matrix. The paths of the allowed energy transfer via optical near-field interactions are illustrated via arrowheads.

As the exciton Bohr radius for cubic CuCl quantum dots aliened in NaCl is small, the translational motion of the exciton center of mass is quantized [7,8]. The difference between potential barriers of CuCl QDs and NaCl barrier is high enough that the exciton energy eigenvalues can be regarded as [1,2,4]:

$$E_{n_x,n_y,n_z} = E_g + \frac{\pi^2 h^2}{2ML^2}(n_x^2 + n_y^2 + n_z^2) \qquad (1)$$

where $L$ is length of cubic QDs, $E_B$ is the energy of the bulk $Z_3$ exciton, $M$ is the mass of the exciton in the translational motion, $a = L - a_B$ corresponds to a QD effective side length for taking the so-called dead layer correction into account [9], in which $a_B$ is its Bohr radius, $n_x$, $n_y$, and $n_z = 1, 2, 3, \ldots$, are the quantum numbers for the center of mass motion. Although the exciton states with at least one even quantum number are dipole-forbidden states and therefore not allowed to enter into an optical far-field interaction [10], they can get involved in localized optical near-field interactions [11].

In Figs. 1 and 2, the effective side lengths of the input dots (QD-A) are the same, i.e., $a_{\text{QD-}A} = a$, for both gates. However, the effective side sizes of the dots (QD-B) and dots (QD-C) in two gates differ from each other. As seen in these figures, these dimensions for QD-B and QD-C of Gate A are $a_{\text{QD-}B} = b = 2^{(1/2)}a$ and $a_{\text{QD-}C} = c = 2a$, respectively; the size ratio is $1 : \sqrt{2} : 2$. The corresponding dimensions of Gate B are $a_{\text{QD-}B} = 1.5^{(1/2)}a$, and $a_{\text{QD-}C} = 3^{(1/2)}a$, respectively; size ratio is $1 : \sqrt{3/2} : \sqrt{3}$. The differences in dimensions have led to the different optical near-field energy transfer paths between adjacent QDs of the two gates. According to Eq. (1) in QDs of Gate A, state (1, 1, 1) of QD-A is in resonance with levels (2, 1, 1) of QD-B and (2, 2, 2) of QD-C, both via optical near-field interactions, whereas level (1, 1, 1) of QD-B is optical near-field coupled solely to (2, 1, 1) of QD-C. As can be seen from Fig. 1, level (2, 2, 1) of QD-C is outmoded. On the other hand, using Eq. (1) in QDs of Gate B one realizes that there are only two unique optical near-field couplings, as shown in Fig. 2. Level (1, 1, 1) of QD-A is in resonance with (2, 2, 1) of QD-C and (1, 1, 1) of QD-B is coupled to (2, 1, 1) of QD-C.

The interaction of an input signal, in either configuration, can facilitate accommodating a Fermionic exciton in level (1, 1, 1) of QD-A. An intra-dot transition from any upper exciton energy level in any QD into its lowest available level, in general, occurs in less than a few picoseconds which is much faster than an inter-dot optical near-field transition. Hence, any possible inter-dot optical near-field transition from the lowest level of each of the QDs to a resonant level of an adjacent QD is nearly irreversible. Such a transition ends by a radiative recombination into the lowest level of the receiving dot [8]. In an OFF state, for either configuration of Fig. 1 or Fig. 2, level (1, 1, 1) of QD-C should be empty. This empty state obstructs the output signal by trapping the input energy. However, in an ON state for either configuration, this level must be occupied by means of a control signal. In that case, the input energy is transferred to the output level ((1, 1, 1) of QD-B in Gate A and (2, 1, 1) of QD-C in Gate B) via a possible combination of inter-dot and downward intra-dot transitions, depending on the gate configuration. The possiblecombinations of OFF and ON