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# All optical controlled-NOT gate based on an exciton–polariton circuit

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We propose an implementation of a CNOT gate for quantum computing based on a patterned microcavity polariton system, which can be manufactured using the modern technological facilities. The qubits are encoded in the spin-coherent polariton states. The structure consists of two wire cavities oriented at 45° with a micropillar between them. The polariton spin rotates due to the Longitudinal–Transverse splitting between polarization eigenstates in the wires. In the pillar, the optically generated circularly polarized polariton macrooccupied state plays the role of the control qubit. Because of the spin-anisotropic polariton interaction, it induces an effective magnetic field along the *Z*-direction with a sign depending on the qubit value.



## 0. Introduction

Quantum computing has evolved a lot since the original idea of Feynmann [1]. Several quantum algorithms outperforming their classical analogs have been proposed and implemented more or less successfully. These algorithms, based on the quantum parallelism, target such problems like factoring large numbers into prime numbers [2], optimization [3], and search [4]. The incredible possibilities offered by quantum computers made the scientists invest a lot of efforts in this field. However, the implementation of these algorithms is haunted by serious obstacles, the most important one being the rapid decoherence of quantum bits (qubits). Various physical implementations of these algorithms

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have been proposed, the most important difference between them being the choice of the physical realization of the quantum states for encoding the qubits. The implementations can be based on discrete quantum states, such as the confined states of the quantum dots [5], on the spin degree of freedom, as in liquid-state nuclear magnetic resonance [6], or on different combinations of the states of Bose–Einstein condensates [7] – the spin-coherent states with a large number of particles [8,9].

All these degrees of freedom can be combined to encode information if one decides to make use of quantum microcavities in the strong coupling regime, and the corresponding 2-dimensional quasi-particles – exciton–polaritons. These particles are a superposition of light (photons confined in the microcavity) and matter (excitons in the quantum wells) [10]. They can be easily created, controlled, and detected using optical means, and their polarization (spin) degree of freedom is easy to manipulate and measure as well [11]. Their in-plane spatial confinement can be organized by patterning the microcavity [12–17] and/or by applying external potentials, which can be created optically [18,19] or induced by surface acoustic waves [20]. Finally, polariton Bose–Einstein condensates are also readily available [21], even at room temperature [19,22], and polariton states with macroscopic occupation can be created by coherent resonant optical excitation [23].

Using polaritons to implement quantum bits provides many advantages. Polaritons, thanks to their photonic fraction, propagate very rapidly, which allows to reduce the problems with decoherence. Their spin relaxation length exceeds hundreds of microns in recent experiments [24,25], while for electrons it is typically several microns [26]. A recent work proposes to use the polariton Rabi oscillations [27] as a basis for qubit representation. This approach, however, is limited by the use of the strongly damped upper polariton branch, which leads to rapid decoherence of the qubit [28], and by the difficulties with the control of the qubit state, requiring large energy shifts. We propose to use the polarization degree of freedom of polaritons to encode information. For example, the circular-polarized $\sigma^+$ state can be assigned a logical 0 ($|0\rangle$), and the $\sigma^-$ state can be assigned a logical 1 ($|1\rangle$). A generic qubit is a superposition $\alpha|0\rangle + \beta|1\rangle$ corresponding, in general, to the elliptic polarization of light. By definition, a quantum gate acts simultaneously on both components of the basis (both circular components). In practice, the state of such a qubit can be modified using effective magnetic fields, well known in quantum microcavities [11]. Such fields can be in-plane, physically induced by the energy splitting which exists between the TE and TM optical modes in planar cavities. In a 1D patterned wire cavities [29], this splitting generally lies between the Longitudinal and Transverse modes. Along the $Z$-direction, a real applied magnetic field can act on polaritons by inducing a finite Zeeman splitting of polariton states [30,31]. A self-induced effective field along the $Z$-direction can also be created due to the polariton–polariton spin anisotropic interaction [32]. Indeed, the polarization degree of freedom of polaritons has already been proposed as a possible solution for the implementation of classical optical logic gates [33].

The use of macrooccupied polariton states for quantum computing was discussed in details in Ref. [7], where the "BEC qubits" were introduced, and later called "spin-coherent states" in Refs. [8,9]. It was shown that such qubits, containing a large number of particles, can be manipulated by quantum gates (with a reduced operation time due to bosonic enhancement), with demonstration of several algorithms. It was demonstrated that the particle decay does not affect the coherence of such qubits: the decoherence is not enhanced by the number of particles, while the operation time is reduced. In our work, we study the practical possible implementation of such gates, passing from abstract Hamiltonian to its realization. The reduced operation time, coming from the large number of polaritons, allows to overcome the dephasing arising from the natural polariton decay.

That a qubit based on polariton spin can be initialized to an arbitrary value and that this value can be maintained for a long time does not need to be proven: such experiments were already carried out [34,24], although the polariton state has not been considered as a qubit in these works. It was shown that the decoherence time for polaritons is much longer than the lifetime. Here, we demonstrate how the two mechanisms of the qubit control based on effective magnetic fields can be combined together in order to achieve the expected operation of the CNOT (controlled NOT) gate. This gate is the essential quantum gate: any quantum algorithm can be implemented using only the CNOT double-qubit gate and single-qubit rotations. We do not study the quantum properties of the CNOT gate in details in the present manuscript, because they were analyzed in principle for quantum gates on spin-coherent states in other works. Instead, we concentrate our efforts on the details of the physical realization,