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# A proposal for the implementation of quantum gates with photonic-crystal waveguides

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**Abstract**

Quantum computers require technologies that offer both sufficient control over coherent quantum phenomena and minimal spurious interactions with the environment. We argue that, photons confined to photonic crystals, and in particular to highly efficient waveguides formed by linear chains of defects, doped with atoms or quantum dots, can generate strong nonlinear interactions between photons allowing for the implementation of both single and two-qubit quantum gates. The simplicity of the gate switching mechanism, the experimental feasibility of fabricating two-dimensional photonic-crystal devices and the integrability of such devices with optoelectronic components offer new interesting possibilities for optical quantum-information processing networks.


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In order to perform a quantum computation one should be able to identify basic units of quantum information i.e., qubits, initialize them at the input, perform an adequate set of unitary operations and then read the output [1,2]. Here we show that these tasks can be efficiently performed using photons propagating along defect chains within photonic crystals. This type of linear defects (defect chains) are known as coupled-resonator optical waveguides (CROWs) [3,4] and provide almost lossless guiding, bending and coupling of light pulses at ultra small group velocities [5–7]. Qubits can be represented by the "dual rail" CROW, i.e. by placing a photon in a superposition of two preselected defect chains such that each chain represents the logical basis state, 0 or 1. Quantum logic gates are then implemented by varying the length and the distance between the CROWs and by tuning the refractive index in some of the defects using external electric fields and cavity QED type enhanced nonlinear interactions between the propagating photons [8–13]. We start with a sketch of the underlying technology followed by a more detailed description of quantum logic gates and conclude with the estimation of the relevant experimental parameters.

Photonic crystals (PCs) are inhomogeneous materials whose relative permittivity is a periodic function in space [14,15]. For wavelengths comparable to the period of the PC they can exhibit photonic band gaps, similar to the electronic band gaps of (atomic) semiconductors. One can also introduce point and linear defects within a PC. A point defect introduces a bound state of the electromagnetic field within the photonic band gap which can act as a high-Q cavity. Many point defects can be brought together to form the above mentioned CROWs. A light pulse which enters a CROW propagates through a tunnelling/hopping mechanism between neighboring defects allowing for a tight-binding-like description of the pulse propagation [3,4,16]. We

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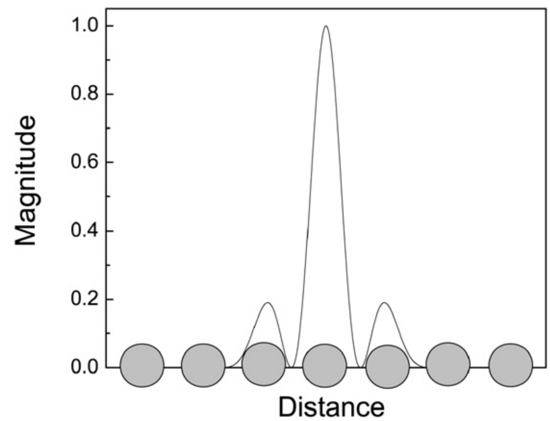


Fig. 1. Snapshot of a pulse propagating inside a CROW. The field intensity is mostly localized inside the defects of the CROW.

note that when a light pulse enters a CROW from free space, its spatial extent contracts to a least one order of magnitude while spending most of its time within a defect before tunnelling to its neighbor [7] (see Fig. 1).

After preselecting two CROWs and labeling them as 0 and 1 we can perform an arbitrary unitary operation on the resulting qubit by concatenating elementary single qubit gates such as the Hadamard gate and a phase shift gate. The Hadamard gate can be implemented by bringing two CROWs of the same qubit closer to each other, about one lattice constant apart, to allow photons to tunnel between them. This process, apart from phase factors, is equivalent to the action of a beam-splitter, or an optical coupler, in conventional optics. A single qubit phase gate can be implemented by increasing the length of one of the two CROWs; the resulting time-delay induces a relative phase shift.

As an example consider a single qubit interference, i.e. a sequence: the Hadamard gate, a phase gate, the Hadamard gate. It can be implemented by a device similar to the one shown in the lower part of Fig. 2, which is essentially a Mach–Zehnder interferometer (MZI) formed by defect chains in a PC. The two Hadamard gates correspond to the two areas in which the CROWs are brought closer to each other. Relative phase $\phi$ can be introduced by varying the length of one of the CROWs in the area between the two Hadamard gates. If a pulse of light is injected into one of the input ports it will emerge at the one of the two output ports with the probabilities $\sin^2(\phi/2)$ and $\cos^2(\phi/2)$, respectively, where $\phi$ is the accumulated phase difference between the two arms. This has been demonstrated experimentally for 2D CROW-based MZIs in the microwave regime [17] as well as for optical telecommunications wavelengths [18,19].

Although the existing experimental realizations of a CROW-based MZIs [17–19] have the phase shift $\phi$ fixed by the architecture, one can introduce an active phase control [20]. This can be achieved by placing a medium with tunable refractive index into one of the arms of the interferometer in between the Hadamard gates. Defects in one of the arms can be doped with atoms or quantum dots of resonance frequency $\omega_{ge}$. These two-level systems can be then tuned to be on and off-resonance with the propagating light of frequency $\omega$ by applying an external electric field, i.e. by using the Stark effect. Initially the

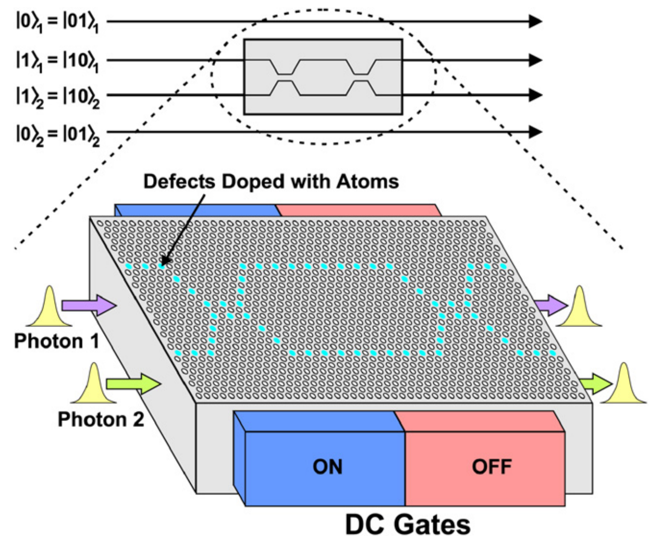


Fig. 2. The upper part shows a schematic of four CROWs which represent two qubits. The two central waveguides, belonging to two different qubits, are brought together in a nonlinear interferometric device which is shown below the schematic. The device is integrated onto a micrometer-sized 2D PC. The defect chains, shown in cyan, transfer photons from left to right. The two defect chains are brought closer to each other right after the entrance and before the exit of the device, allowing photons to tunnel between them. The defects in between these two regions are doped with atoms or quantum dots which can be tuned to be on- and off-resonance with the propagating light by applying an external electric field. An interplay between (resonant) two-photon and (dispersive) one-photon transitions leads to phase shifts required both for single-qubit phase gates and two-qubit controlled-phase gates. The blue and pink boxes mark the area where the electric field is on and off, respectively. When the field is switched on it induces a nonlinear phase shift. However, at the end of the quantum gate operation the field is selectively turned off to the right of the defect where the phase shift was induced, allowing photons to be released back to the propagating modes. (For interpretation of the references colour in this figure legend, the reader is referred to the web version of this article.)

dopants are far off resonance with the light pulse allowing the pulse to enter the CROWs without any reflections. As soon as the pulse reaches the area in between the Hadamard gates the electric field is applied bringing the dopants closer to resonance and inducing a near-resonant dispersive interaction. When the detuning $\delta = \omega_{ge} - \omega$ is smaller than both $\omega$ and $\omega_{ge}$ and, at the same time, much larger than the coupling constant between the dopant and the light field $\Omega$, i.e. when $\omega_{ge}, \omega \gg \delta \gg \Omega$, the combined dopant-light system acquires a phase proportional to $(\Omega^2/\delta)T$, where $T$ is the interaction time. Both $\delta$ and $T$ can be externally controlled and, this way, one can introduce any desired phase shift between the two arms of the interferometer.

Let us now show how the device shown in Fig. 2 can be used to implement a two-qubit conditional phase gate. The two qubits are represented by four CROWs labelled as $|0\rangle_1$, $|1\rangle_1$ and $|0\rangle_2$, $|1\rangle_2$ respectively for the first and the second qubit. Only two of the four CROWs enter the device. They have labels $|1\rangle_1$ and $|1\rangle_2$ and represent the binary 1 of the first and the second qubit. Thus the device operates either on vacuum (input $|0\rangle_1|0\rangle_2$), or on a single photon (inputs $|0\rangle_1|1\rangle_2$ and $|1\rangle_1|0\rangle_2$) or on two photons (input $|1\rangle_1|1\rangle_2$). The desired action of the device, i.e. the conditional phase shift gate, is: $|0\rangle_1|0\rangle_2 \to |0\rangle_1|0\rangle_2$, $|0\rangle_1|1\rangle_2 \to |0\rangle_1|1\rangle_2$, $|1\rangle_1|0\rangle_2 \to |1\rangle_1|0\rangle_2$, $|1\rangle_1|1\rangle_2 \to -|1\rangle_1|1\rangle_2$. This means that the device allows the