Photonic chips for quantum communication

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Introduction

Are you familiar with the concept of information transfer or communication through means such as internet, wireless communication, or other types of networks? One of the fundamental limitations of all these communication methods is that they cannot transmit information faster than the speed of light, which is about 300k meters per second. Nowadays, world revolves around data and information, the speed with which we are able to process and compute it is the key to nearly all future science advancements and currently, increasing its efficiency is one of the key goals in science. This limitation can be seen very clearly in the aspect of space exploration. The downward bound of the latency between Earth and Moon due to the lightspeed is on the level of 1.5s, between Earth and Mars from 3.5m to ca 22m – depending on the positions of the planets on theirs orbits. So the question is if the faster than light communication is possible?

There is a phenomenon in quantum mechanics known as *quantum entanglement* that has been theorized to allow for faster-than-light (FTL) communication, described e.g. by Tann in [1] or Mazurek et al. in [2]. It refers to a situation where two particles become "entangled" with each other, meaning that the eigen-state after measurement of one particle is dependent on the state of the other, no matter how far apart they are. The physical foundations of this phenomenon lays in the fact, that there exists a d-dimension system state appearing in an irreducible form, which means that it cannot be achieved as a composition (*tensor product*) of two or more less complex (dimension) systems. Basing on that phenomenon and on other ones (like superposition and interference) there is possible to create a set-up, called *quantum teleportation* (e.g., Mafi et al. [3] or Lago-Riviera et al. [4]), which is the foundation of quantum communication and FTL.

Roughly and very informal speaking, the process of FTL would involve creating two entangled particles (most cases: photons) and then sending one of them to a distant location while keeping the other one with you. If you then measure the state of one of them, the state of the distant particle would be instantly determined. This could be used to transmit information, with the state of the distant photons, which polarization represents the information being transmitted.

Another very interesting approach which we would like to pursue in terms of data transmission, are photonic technologies, announced and implemented by Xanadu (e.g., Bourassa et al. [5] or Arrozola et al. [6]), which are based on so called *squeezed light* (SL). The other solutions are currently available from Quantum QuiX based on single photon sources (SPS) described by Taballione et al. [7] or on quantum dots sources (QDS), described by deGoede et al. [8]. They all offer a way to revolutionize the information transfer using light instead of traditional electronic signals. They are used in a variety of applications, including fiber-optic communication networks, laser-based manufacturing processes, and biomedical imaging. Needless to say, they offer several advantages over traditional electronic communication, including higher bandwidth, lower power consumption, and less susceptibility to interference.

When combined with quantum links, they can enable secure communication between two parties, even over long distances. As mentioned earlier, when two particles are entangled, their properties become linked and transferred between one another. This allows for the creation of a secure communication channel, as any attempt to intercept the communication will disrupt the entanglement and alert the parties involved to the presence of an intruder.

The photonic chip

The name *photonic* is the composition of *photon* and *electronic*, which means that it has two layers: (1) optical one supplied by a photon source mentioned in the introduction: SL, SPL or QDS, and (2) the electronic one, that is used for steering the miniaturized optical devices. Those two layers allows to create *dynamic* optical circuit, which means that they can be changed during the light travels in a waveguides. They have a practical application in the construction of devices for the optical-fiber

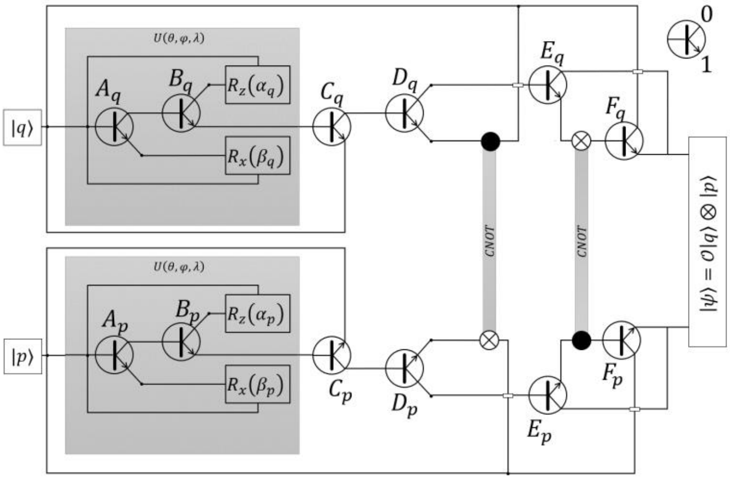

Figure 1. The quantum optical circuit that realizes all two-qubit operations that can be made using Universal, one qubit gate and CNOT gate. It is an example of reusability of gates. It is not said that this circuit will be used during test.

networks e.g., switches allowing to exclude the bottleneck appearing in the optic-silicon and silicon-optic connections. Nevertheless they are answer for the two challenges with optical circuits used for quantum computation, expressed by Kok et al. in [9]. The problem with exponential growth of the devices which we have to use, in reference to linear growth of qubits, can be resolved by light routing though the same devices on a chip. The chip equipped with optical switches or their arrays, that with the electronic layer avails to establish the route of the light realizing arbitrary quantum circuit made of the set allowed quantum gates. On the Figure 1 there is a scheme of exemplary quantum optical circuit that uses two one qubit gates (R_x,R_z) for each qubit, two CNOT gate pined to two input qubits crosswise, and twelve optical switches (six per qubit). Universal one qubit gate can be constructed as follows: $U(\theta,\varphi,\lambda) = R\_z\ (\varphi+\pi/2)\ R\_x\ (\theta)R\_z(\lambda-\pi/2)$. It can be realized (for qubit $|q\rangle$) by this circuit in four iterations: (1) $A_q \leftarrow 0$; $B_q \leftarrow 0, \alpha_q = \varphi + \pi/2$, (2) $A_q \leftarrow 1$; $\beta_q = \theta$, (3) $A_q \leftarrow 0$; $B_q \leftarrow 0, \alpha_q = \lambda - \pi/2$, (4) $A_q \leftarrow 0$; $B_q \leftarrow 1; C_q = D_q = E_q = 0$. In that case $|\psi\rangle = [U(\theta,\varphi,\lambda) \otimes 1]|qp\rangle$. There are some challenging issues connected with implementation of light routing. First, there is a problem of synchronization of the laser impulse with switching. In the first stage of research, we will use low laser frequencies, short circuits, and long routs to separate consecutive shots in time. However, the long-term aim is to be able maintain several shots in one physical circuit, without influence between different shots. We assume here that we have the same quantum program in a physical circuit, which simplifies the task. For this purpose, there will be designed more suitable solutions consisting of gate vectors and switches' matrices developed in mid-or long term. It allows to create parallel routs of quantum processing. In the second stage of this project, we plan to construct such a unit of small sizes – up to 4 gates in a vector and 4×4 optical switches to maintain small number (2-4) of shots at the time. Secondly, we can expect that the fidelity of the state lowers over time due to many phenomenon, like detuning, decoherence, noise, system inaccuracies, etc.

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