Scheme for a linear-optical controlled-phase gate with programmable phase shift

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Abstract
We present a linear-optical scheme for a controlled-phase gate with tunable phase shift programmed by a qubit state. In contrast to all previous tunable controlled-phase gates, the phase shift is not hard-coded into the optical setup, but can be tuned to any value from 0 to π by the state of a so-called program qubit. Our setup is feasible with current level of technology using only linear-optical components. We provide an experimental feasibility study to assess the gate’s implementability. We also discuss options for increasing the success probability up to 1; this approaches the success probability of an optimal non-programmable tunable controlled-phase gate.

Keywords: programmable gate, quantum gate, controlled-phase gate, linear optics

1. Introduction

Quantum computing is a promising approach, which has the potential to considerably improve computing efficiency [1, 2]. It has been demonstrated that any quantum circuit can be decomposed into a set of standard single- and two-qubit gates [3]. While the single-qubit gates represent single qubit rotations, the two-qubit gates make the qubits interact and thus process information. A prominent example of such a two-qubit gate is the controlled-phase gate (or its close relative, the controlled-NOT gate) [4].

The controlled-phase gate performs the following transformation on the target and control qubit states:

\[
\begin{align*}
|00\rangle & \to |00\rangle, \\
|01\rangle & \to |01\rangle, \\
|10\rangle & \to |10\rangle, \\
|11\rangle & \to e^{i\varphi} |11\rangle,
\end{align*}
\]

(1)

where 0 and 1 in the brackets stand for logical states of both the target and the control qubits, respectively. The parameter \(\varphi\) then denotes the introduced phase shift. There have been a number of experimental implementations of the controlled-phase gate achieved on various physical platforms, including nuclear magnetic resonance [5], trapped ions [6], and superconducting qubits [7]. On the platform of linear optics, this gate has been implemented using various schemes [8–10] (for review papers see also [11, 12]). All these implementations, however, only considered phase shift \(\varphi = \pi\), also known as the controlled-sign transformation.

Operating the controlled-phase gate at phase shifts other than \(\pi\) was investigated for the first time in a seminal paper by Lanyon et al (2009) [13]. In order to achieve diverse phase shifts, the authors increased the Hilbert space by introducing auxiliary modes. Their implementation, however, does not have optimal probability of success. In 2010, Konrad Kieling et al proposed a scheme for an optimal linear-optical C-phase gate with tunable phase shift [14]. In 2011, this scheme was experimentally implemented and tested in our laboratory [15]. Both the Lanyon et al [13] scheme and our own [15] have the phase-shift hard-coded by the specific settings of various optical elements. But these limit the adaptability and usefulness of these gates in multipurpose quantum circuits.

In order to make quantum circuits more versatile, researchers have proposed so-called programmable gates [16]. Instead of hard-coding the transformations into the experimental setup, these gates have their properties programmed by the quantum state of the so-called program qubit. While it would be necessary to use an infinite amount of classical information, one qubit of quantum information suffices to precisely set a real-valued parameter of a quantum gate (or transformation). Such qubit can also be transmitted.
over a quantum channel, thus allowing for remote programming of a quantum gate similar to classical software distribution over computer networks. The quantum transformation in question is basically teleported to its user.

As a proof-of-principle, Mićuda et al have constructed a programmable phase gate [17]. This gate introduces a programmable phase shift between the logical states $|0\rangle$ and $|1\rangle$ of a signal qubit. Thus it achieves programmable single-qubit rotation along one axis. The success probability of this scheme has been recently improved to the theoretical limit of 1/2 using feed-forward [18].

In this paper, we propose a linear-optical scheme for a tunable C-phase gate with programmable phase shift. This is not to be confused with the programmable phase gate [17, 18], where only single-qubit rotation was programmed, while in our case we program a two-qubit operation by means of a third qubit. A tunable C-phase gate is a key ingredient for a number of protocols, including quantum routers [19, 20], quantum state engineering [21, 22], and controlled-unitary gates [13, 23]. By adding the programmability, we further develop this important gate, making it a more versatile, and, therefore, an even more powerful tool for quantum information processing. Also note that since single qubit rotations and controlled-phase gate are sufficient to construct any quantum circuit, the proposed programmable controlled-phase gate with already known programmable single-qubit rotations allow, in principle, the construction of any programmable quantum circuit. The conceptual scheme of the proposed gate is shown in figure 1. We adopt the following notation throughout the paper: $|\psi_T\rangle$, $|\psi_C\rangle$, and $|\psi_P\rangle$ denote the target, control, and program qubits, respectively. The program qubit takes the form of

$$|\psi_P\rangle = \frac{1}{\sqrt{2}}(|0\rangle - e^{i\varphi}|1\rangle),$$

where $\varphi$ is the phase shift to be introduced by the gate if both the target and control qubits are in the logical state $|1\rangle$ as requested by the gate’s definition (see equation (1)). The program qubit is destroyed by detection in the process while the target and control qubits leave the gate and can be used for further processing.

The paper is organized as follows: In section 2 we derive the basic functioning of the gate. In section 3 we show what techniques can be used to increase the success probability of the scheme. Finally, in section 4, we discuss the scheme’s experimental feasibility.

2. Linear-optical scheme

A linear-optical scheme for a C-phase gate with programmable phase shift is depicted in figure 2. In this scheme, we consider encoding logical states $|0\rangle$ and $|1\rangle$ into horizontal (H) and vertical (V) polarization states of individual photons. We also introduce an auxiliary mode that is similar to the Lanyon et al gate [13], but we also introduce an auxiliary mode. In our case, however, we use this mode for interaction between the target and program qubits. In this section, we describe the principle of operation of the gate for all four basis states defined in equation (1) and an arbitrary phase shift $\varphi$ set in the program qubit (2). The gate is necessarily probabilistic (all linear-optical C-phase gates are [14]). Its successful operation is demonstrated by the observation of one photon at each of the target and control output ports, and also by the detection of a photon on detector D. Let us start with the evaluation of the state $|00\psi_P\rangle$ (we maintain the order of qubits: target, control, and program). The target photon impinges on the polarizing beam splitter (PBS$_s$) that sends it to the upper path. There the target photon is subjected to a neutral density filter $F_1$ with amplitude transmissivity $t_{F1} = \frac{1}{2}$ and subsequently continues to the target output port by passing through the second polarizing beam splitter PBS$_2$. So far, one can write

$$Figure 1. Conceptual scheme of a programmable C-phase gate. $T$, $C$ and $P$ denote target, control, and program ports, respectively. The phase shift $\varphi$, encoded into the state of the program qubit, is equivalent to the phase shift introduced by the gate (equation (1)).

Figure 2. Linear-optical setup for the C-phase gate with programmable phase shift. The target, control, and program qubit enter the setup at $T_{IN}$, $C_{IN}$, and $P_{IN}$, respectively and the target and control output are denoted as follows: $T_{OUT}$ and $C_{OUT}$. The program qubit is detected by polarization-sensitive detector D by projecting it onto diagonally polarized state. PBS$_s$ ($x = 1, 2, 3$) transmit horizontally polarized photons while reflecting vertical polarization. PPBS has unit transmissivity for horizontal polarization and $k_1 = 1/\sqrt{3}$ for vertical polarization (therefore the reflectivity for vertical polarization is $r_1 = \sqrt{2/3}$). Filter $F_1$ is a neutral density filter with amplitude transmissivity $t_{F1} = \frac{1}{2}$ while the filter $F_2$ only filters horizontal polarization with transmissivity $t_{F2H} = 1/\sqrt{3}$. Half-wave plates (HWP) (HWP) are rotated with respect to horizontal polarization by angles: $\theta = -9.2^\circ$, HWP$_2$ and HWP$_3$, $\theta = 22.5^\circ$. The gate succeeds if one photon leaves by the target output port, one photon by the control output port and one photon is detected by detector D.
down the transformation of the state as
\[ |00\psi_p\rangle \rightarrow \frac{1}{2} |00\psi_p\rangle. \]

Meanwhile the control photon is transmitted by the partially polarizing beam splitter (PPBS) (with transmissivity \( t_H = 1 \) for horizontal polarization and \( t_V = \sqrt{1 - t_H^2} = \frac{1}{\sqrt{3}} \) for vertical polarization) and after being subjected to polarization filtering by the filter \( F_3 \) (filtering horizontal polarization with transmissivity \( t_{fH} = \frac{1}{\sqrt{3}} \) and letting the vertical polarization unfiltered \( t_{fV} = 1 \)) it leaves the setup by the control output port. At this point the transformation by the gate reads:
\[ |00\psi_p\rangle \rightarrow \frac{1}{2\sqrt{3}} |00\psi_p\rangle. \]

Finally, the program photon impinges on PBS3, where it gets transmitted and reflected with equal amplitude \( 1/\sqrt{2} \). Since the gate only succeeds if a photon is detected on detector D, it is only necessary to take into account the transmission of the program photon through PBS1. Considering that the program photon is in the state (2), the overall state gets transformed into
\[ |00\psi_p\rangle \rightarrow \frac{1}{2\sqrt{6}} |000\rangle. \]

Once the program photon leaves PBS3, we project it onto diagonal polarization \( |D\rangle = \frac{1}{\sqrt{2}}(|0\rangle + |1\rangle) \), resulting in the final form of the transformation:
\[ |00\psi_p\rangle \rightarrow \frac{1}{4\sqrt{3}} |000D\rangle. \]

This projection is needed to erase the which-path information about the photon detected on detector D. In the same way, we now evaluate the transformation of the second state \( |01\psi_p\rangle \). The only difference this time is in the control qubit. It impinges on the PPBS having vertical polarization and is therefore transmitted with amplitude \( \frac{1}{\sqrt{3}} \) and reflected with amplitude \( \frac{\sqrt{2}}{\sqrt{3}} \). Only the transmission of the control photon by the PPBS contributes to the successful operation of the gate. Furthermore, no attenuation of the vertically polarized control photon takes place on \( F_2 \). By using the same transformation for the target and program qubits as in the previous paragraph, one can identify the overall action of the gate
\[ |01\psi_p\rangle \rightarrow \frac{1}{4\sqrt{3}} |01D\rangle. \]

The third state \( |10\psi_p\rangle \) is a different matter. The target photon is reflected by PBS1 entering the lower path, where it is subjected to an HWP1 oriented by \( -9.2^\circ \) with respect to horizontal polarization. This wave plate transform the target photon in the following way:
\[ |1\rangle \rightarrow \frac{1}{2} |0\rangle + \frac{\sqrt{3}}{2} |1\rangle \]
and thus causes the overall state to get transformed into
\[ |10\psi_p\rangle \rightarrow \frac{1}{2} |00\psi_p\rangle + \frac{\sqrt{3}}{2} |10\psi_p\rangle. \]

At this point, the target and control photons interact on the PPBS. Since the control photon is transmitted through the PPBS (having horizontal polarization in this case), we only take into account the transmission of the target photon to ensure successful outcome of the gate
\[ |10\psi_p\rangle \rightarrow \frac{1}{2\sqrt{3}} |00\psi_p\rangle + \frac{1}{2\sqrt{3}} |10\psi_p\rangle, \]
where we have already incorporated the action of the polarization-sensitive filter \( F_2 \). Now the target state enters a Hadamard transform implemented by an HWP2 rotated by \( 22.5^\circ \) with respect to horizontal polarization, providing target photon transformation of the form of
\[ |0\rangle \rightarrow \frac{1}{\sqrt{2}} (|0\rangle + |1\rangle) \]
\[ |1\rangle \rightarrow \frac{1}{\sqrt{2}} (|0\rangle - |1\rangle), \]
which then translates into the overall state evolution
\[ |10\psi_p\rangle \rightarrow \frac{1}{\sqrt{6}} |00\psi_p\rangle. \]

The target photon passes through PBS3 having horizontal polarization. Thus, as in the cases derived above, the gate can only succeed if the program photon passes through the PBS3 and then gets projected onto diagonal polarization. Thus we obtain the transformation in the form of
\[ |10\psi_p\rangle \rightarrow \frac{1}{2\sqrt{6}} |00D\rangle. \]

Finally, the target photon is again subjected to a Hadamard transform (HWP3), resulting in
\[ |10\psi_p\rangle \rightarrow \frac{1}{4\sqrt{3}} (|00D\rangle + |10D\rangle). \]

Only the target photon reflected by the PBS3 leaves the gate, by designated output port, and thus we obtain the final form of the transformation:
\[ |10\psi_p\rangle \rightarrow \frac{1}{4\sqrt{3}} |10D\rangle. \]

To complete our analysis, we now evaluate the transformation of the last basis state \( |11\psi_p\rangle \). As in the previous case, the target photon gets reflected on PBS1 and transformed by the HWP1 according to equation (5). The overall state thus takes the form of
\[ |11\psi_p\rangle \rightarrow \frac{1}{2} |01\psi_p\rangle + \frac{\sqrt{3}}{2} |11\psi_p\rangle. \]
where only the terms contributing to success of the gate are shown. Note that when both the target and control photons enter the PPBS in vertical polarization state, the interference of both the photons being transmitted and the photons being reflected (Hong–Ou–Mandel interference) occurs, which introduces a phase shift $\pi$ to the term $|11\psi_r\rangle$ [10]. By means of the subsequent Hadamard transform in the target mode (HWP$_2$), the state transforms into

$$|11\psi_r\rangle \rightarrow \frac{1}{\sqrt{6}} |11\psi_r\rangle.$$ 

On PBS$_3$ the target photon gets reflected (being vertically polarized) and so only the program photon reflection can contribute to the gate’s successful operation. This means that only its vertical polarization term contributes yielding the overall state in the form of

$$|11\psi_r\rangle \rightarrow -e^{i\phi} \frac{1}{2\sqrt{3}} |111\rangle,$$

which, after projecting the photon in program mode onto diagonal polarization, gives

$$|11\psi_r\rangle \rightarrow -e^{i\phi} \frac{1}{2\sqrt{6}} |11D\rangle.$$

Action of the Hadamard gate in the target mode (HWP$_3$) and reflection of the target photon on PBS$_2$ to its output port results in the final transformation:

$$|11\psi_r\rangle \rightarrow e^{i\phi} \frac{1}{4\sqrt{3}} |11D\rangle.$$

In contrast to the three previous cases, the state is now phase-shifted by angle $\phi$ exactly as prescribed in (1).

We have shown that the setup depicted in figure 2 implements the tunable C-phase gate with the phase shift programmed by the program qubit. The overall action can be summarized by the following formula:

$$|xy\psi_r\rangle \rightarrow \frac{1}{4\sqrt{3}} e^{ixy\phi} |xyD\rangle,$$

where $x, y = 0, 1$. This has been demonstrated on all four basis states of the control and target qubits together with an arbitrary program state. Since all transformations are linear, the entire operation holds also for any superposition of the these four basis states. The success probability of the gate is $1/(4\sqrt{3})^2 = \frac{1}{48}$ and is state-independent in order to avoid deforming the superpositions of basis states. In the next section, we will consider potential improvements to the setup in order to increase the success probability.

3. Increasing the success probability

We have discussed the basic scheme for the programmable C-phase gate, which is the simplest to implement in the laboratory. On the other hand, its success probability is more than four times lower then the success probability of the optimal non-programmable C-phase gate. In this section, we will discuss two optimization approaches that will result in considerable improvement in success probability (figure 3).

For example, one can increase the success probability by extending the set of projections used for detecting the program photon. As derived in the previous section, the gate succeeds if the program photon is projected onto diagonal polarization and detected by D. This way, we neglect half of the cases corresponding to the program photon being projected onto anti-diagonal polarization $|A\rangle = \frac{1}{\sqrt{2}}(|0\rangle - |1\rangle)$. As experimentally demonstrated on a simpler unconditional programmable gate [18], it is possible increase the success probability by a factor of two if the anti-diagonal projections of the program photon are included. In such cases, a feed-forward transformation $|1\rangle \rightarrow -|1\rangle$ has to be applied to the target photon immediately as it exits PBS$_3$ [24]. Such a transformation can be achieved by using, for instance, a phase modulator (PLM) [18].

Alternatively, one can also increase the overall success probability by a factor of two by using both the output ports of PBS$_2$ (designated T$_{OUT1}$ and T$_{OUT2}$ in figure 3). In this case, the amplitude transmissivity of the filter F$_1$ shall be reduced to $t_{F1} = \frac{1}{\sqrt{2}}$ and an HWP$_4$ inserted behind it. This newly added wave-plate is rotated by $22.5^\circ$ with respect to horizontal polarization to implement the Hadamard transform (6). The target state at T$_{OUT1}$ is thus kept unchanged, but it allows for the target photon to leave also by the output port T$_{OUT2}$. The target photon exiting PBS$_2$ by its second output is deforming the superpositions of basis states. In the next section, we will consider potential improvements to the setup in order to increase the success probability.
4. Experimental feasibility

In this section, we discuss the feasibility of the proposed scheme based on the current level of technological development in linear-optical quantum information processing with discrete photons. First, in order to achieve any linear-optical quantum gate, one needs to generate an adequate input photon state. Our gate requires three photons, each bearing one polarization-encoded qubit. The generation of three separate photons has already been achieved in various experiments. Either one photon pair from spontaneous parametric down-conversion (SPDC) is combined with one additional photon from attenuated fundamental laser beam [25] or two photon pairs are generated via SPDC with one photon serving just as a trigger [20]. With either of these techniques, one can generate input states with sufficient fidelity, typically more than 95%. Repetition rate at the output of experimental setup is typically 0.01–0.1 Hz [26, 27].

In the next step, we assess the feasibility of stabilizing the proposed scheme. There are two types of stabilizations required: two-photon temporal and spatial overlap stabilization (Hong–Ou–Mandel interference [28]) and single-photon interference stabilization. The overlap stabilization requires the precision of about 1/50 of the photon wave packet full width at half maximum (FWHM) which is typically 100 μm. One can use motorized translation to achieve this task and the adjustment remains stable for hours. On the other hand, the single-photon interference typically needs to be stabilized to at least λ/50, where λ is the photon’s wavelength. Such precision requires the combination of both motorized translation for larger steps and piezo translation for fine adjustments. In a typical bulk interferometer on decimeter scale, the single-photon stability lasts for less than a minute [15]. One can significantly increase the duration by replacing a classical interferometer with a more compact design [29].

Finally, the feasibility considerations have to be dedicated to the final detection procedure. The detection has to be robust against non-unit quantum detection efficiency of typical detectors and technological losses (e.g., back-reflection and coupling efficiency). This requirement rules out vacuum detection-based schemes (schemes where success is demonstrated by vacuum detection or no detection) [30]. Similarly, photon-number resolving detection is not completely reliable because of detection inefficiency [31] and technological losses. In our case, however, the scheme only requires post-selection on three-fold coincidence detections, thus, the quantum efficiency of the detectors only affects the detection rate and not the detected quantum state. This is yet another key feature that contributes to the feasibility of the proposed scheme.

It should be noted that our scheme can also be implemented on the platform of integrated optics. In contrast to the traditional bulk-optical platform, integrated optics brings many interesting benefits including the inherent stability of interferometers and the possible usage in practical quantum information-processing devices. Recent developments in this field makes us confident that the proposed scheme is well within reach. For instance, single-photon and two-photon interferometers with adjustable phase shifts have been achieved experimentally [27]. Simultaneously, investigators have already demonstrated complete control over polarization-encoded qubits in integrated optical circuits [32, 33].

5. Conclusion

In this paper, we have provided a linear-optical scheme for a programmable C-phase gate. The phase shift introduced by this gate is set by the state of a program qubit, which makes the gate more versatile than previously implemented tunable C-phase gates with phase shift hard-coded to the equipment setting. The setup is designed with experimental feasibility in mind. It does not require photon-number resolving detectors or post-selection on vacuum detection. Therefore, it is feasible given the current understanding of experimental linear-optical quantum information processing.

We have also presented two optimization options. Each of them doubles the overall success probability of the gate. Using both of these optimizations, the gate succeeds with probability of 1/12, which is close to the success probability of a non-programmable tunable C-phase gate [15]. Furthermore, the two optimization steps can be used independently. If only one of them is used, the success probability equals 1/24. The first optimization method consists of applying an experimentally feasible feed-forward operation. The second optimization method involves using both output ports of the final polarizing beam splitter in the target mode.

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