Integrated programmable controlled phase gate design for quantum information processing

Yalın Başay and Serdar Kocaman

1 Micro and Nanotechnology, Middle East Technical University, Ankara, Turkey
2 Electrical – Electronics Engineering, Middle East Technical University, Ankara, Turkey

E-mail: basay.yalim@metu.edu.tr and skocaman@metu.edu.tr

Keywords: linear optical quantum computing, integrated optics, CPHASE gate, polarization rotator

Abstract

An integrated programmable controlled-phase (CPHASE) gate has been proposed for quantum information processing applications. This gate can introduce arbitrary phase difference to the target qubit in the case of the control qubit being in the state of $|1\rangle$. As the desired phase difference can be utilized after fabrication, unlike the conventional controlled-phase gates that provide hard-coded phase shift, such an integrated gate is expected to pave the way for more versatile operations of current integrated optical circuits as well as possible new applications.

1. Introduction

Research on quantum information technologies is an interesting topic since it promises unique applications by taking advantage of quantum phenomena such as superposition and entanglement. These efforts started to yield outcomes that cannot be classically achieved [1, 2]. Although these results have a limited area of usage, more crucial applications, especially in the fields of cryptography and secure communication, are expected to be achieved in the near future [3]. Besides long-standing efforts of implementing quantum information processing via trapped ions [4, 5] or superconductors [6, 7], linear optical quantum information processing, which is a relatively new field, demonstrates an outstanding performance. Photons are preferable carriers of quantum information that have little interaction with the environment. On the other hand, they do not directly interact with other photons. Therefore, it is not easy to implement two-qubit gates essential to achieve universal quantum computation. However, an interaction-like behavior by using ancilla photons makes photonic two-qubit gates achievable [8, 9]. This opportunity leads to a vast amount of research on linear optical quantum information processing that offers advantages such as more durability of photons to decoherence and the potential to link quantum computation and quantum communication in the same framework. By encoding quantum information to various degrees of freedom of photons such as polarization [10–12], orbital angular momentum [13–15], time-bin [16–18], frequency [19, 20] and path [21–23], researchers have been making great progress towards large scale photonic quantum computation as well as applications as quantum key distribution [24], quantum random number generation [25] and quantum simulation [26, 27].

Moreover, a complete set of universal gates should be implemented to achieve universal quantum computation. The focus of most of the research is the realization of controlled-not (CNOT) gate [28, 29] usage of which with single-qubit rotations leads to universal quantum computation. SWAP gate [30–32], which eases implementation, and CPHASE gate [33] are also prominent candidates to achieve this. An advantage of the CPHASE gate is that it is possible to introduce the desired phase difference between two quantum states. This phase difference can either be fixed [34] or determined during the operation [35]. The latter case provides more versatile quantum circuits by introducing program qubits to supply the desired phase difference. Offering miniaturized and more stable structures compared to bulk counterparts, integrated quantum photonics is a promising platform for achieving scalable quantum operations [36]. In literature, many studies focus on the integration of CNOT gates and circuits based upon them [37, 38], while designs for CPHASE gates are relatively rare [39]. Here, we demonstrate integrated optical implementation of the CPHASE gate with a programmable
phase shift. We used a unique and practical polarization rotator that was recently proposed by Xu et al to implement half-wave plates in this scheme [40].

What is expected from a tunable CPHASE gate is to introduce an arbitrary phase shift which is determined by the program qubit, in the case of both target and control qubits being in the state of $|1\rangle$. In other words, it adds the desired phase difference between $|0\rangle$ and $|1\rangle$ states of the target qubit if the control qubit is in the state of $|1\rangle$. This operation can be achieved probabilistically but heralded by using polarization encoded qubits. In [35], an optical setup for tunable CPHASE operation is designed such that the success of the operation depends on the observation of one photon at each of the target and control outputs and detection of a photon on a detector. This setup outputs the program qubit instead of target qubit whenever both control and target qubits are in $|1\rangle$ state, and output the original target qubit for all other cases. Because of indistinguishability of photons, this process is equivalent to add phase to target qubit. This means that in ideal lossless case all input states are mapped to desired outputs (as expected from a CPHASE gate), so the fidelity is 100%, in other words the gate does not approximate the desired mapping but realizes exact mapping between input and output states. The scheme of such a circuit is shown in figure 1. Optical elements used in this scheme are three polarizing beam splitters (PBS$_1$, PBS$_2$, PBS$_3$), one partially polarizing beam splitter (PPBS), two filters (F$_1$, F$_2$) and three half-wave plates (HWP$_1$, HWP$_2$, HWP$_3$). PBS$_1$, PBS$_2$ and PBS$_3$ transmit horizontally polarized photons while reflecting vertically polarized ones. PPBS has unit transmissivity for horizontal polarization while transmissivity of $1/\sqrt{3}$ for vertical polarization, F$_1$ has amplitude transmissivity of $1/2$, F$_2$ only filters horizontal polarization with a transmissivity of $1/\sqrt{3}$, and finally, transformations performed by three half-wave plates are following:

For HWP$_1$:

$$|1\rangle \rightarrow \frac{1}{2}|0\rangle + \frac{\sqrt{3}}{2}|1\rangle$$

For HWP$_2$ and HWP$_3$:

$$|0\rangle \rightarrow \frac{1}{\sqrt{2}}(|0\rangle + |1\rangle)$$

$$|1\rangle \rightarrow \frac{1}{\sqrt{2}}(|0\rangle - |1\rangle)$$

In this scheme, an incoming photon from T$_{IN}$ is expected to be transmitted to the upper arm if it is horizontally polarized or reflected to the lower arm otherwise after the input to PBS$_1$. After this separation of states, a horizontally polarized state is subjected to F$_1$, which filters some portion of its amplitude to equalize output amplitude with the amplitude of states processed at the lower arm. In the meantime, the vertically polarized state at the lower arm reaches HWP$_1$ and transforms to a superposition of two polarization states which is a requirement for successful operation. In particular, if C$_{IN}$ is in the $|0\rangle$ state while the other input of PPBS is $|1\rangle$, both photons will output from C$_{OUT}$, so no successful operation will be possible for this combination. The most critical part of the scheme is the PPBS, where quantum interference occurs if both target and control qubits are in $|1\rangle$ state. In this way, a phase difference of $\pi$ emerges between $|0\rangle$ and $|1\rangle$ states. As a result of this phase difference, the outcome of HWP$_2$ becomes $|1\rangle$, which would be $|0\rangle$ if there was no phase difference, and the detector detects the $|1\rangle$ state since it is reflected at PBS$_2$. Because the success of the operation depends on detection at the detector, which is satisfied now, $|1\rangle$ state of program qubit that has desired phase, enters the lower arm of the circuit and output from T$_{OUT}$ after being subjected to HWP$_3$. The function of HWP$_3$ here is to ensure some portion of $|0\rangle$ state turns into $|1\rangle$ state to be reflected at PBS$_2$ and outcome from T$_{OUT}$. The detailed mathematical steps of the operation are explained in [35].

2. Design and results

To construct this scheme as a photonic integrated circuit, all elements mentioned above should be designed appropriately and then combined. We performed finite-difference-time-domain simulations with MEEP [41].

Figure 1. Scheme of programmable controlled phase gate.
for 1.55 $\mu$m wavelength in 350 nm $\times$ 350 nm silicon-on-insulator (silica is used as an insulator) waveguides. Directional couplers are used as beamsplitters, with a 250 nm gap in coupling regions. The beam splitter’s transmissivity and reflectivity values can be implemented by modifying coupler lengths since coupling rates are different for vertical and horizontal polarizations due to the slight birefringence, as shown in figure 2. Here, the length of one cycle is 35.80 $\mu$m for $E_x$ (horizontal polarization) and 8.32 $\mu$m for $E_z$ (vertical polarization). From our calculations, for PBS1, PBS2, and PBS3, the coupling length turns out to be 70.72 $\mu$m, and for PPBS, it is 35.90 $\mu$m. A similar approach helps construct an integrated filter function to get rid of some proportion of light. This purpose can be achieved by transferring the desired proportion of light to a waveguide that removes it from the circuit. For $F_1$, since we expect that vertically polarized light reflected to lower arm at PBS1, so vertical polarization reaching the filter is already a probabilistic failure of the gate, only horizontal polarization can be considered. The length of the coupling region, after which the energy of horizontal polarization drops to one-fourth of the initial value, is 12.00 $\mu$m. Lastly, for $F_2$, one-third of the energy of horizontal polarization and all of the vertical polarization should stay in the initial waveguide. After performing similar calculations, 83.20 $\mu$m is necessary for such an operation.

As half-wave plates, we use the notched ring resonator that was recently proposed at [40]. Racetrack geometry shown in figure 3(a) is used to ensure all light transfers to the structure. Note that the radius of the curved part, which is precisely a half-circle, is 8.00 $\mu$m. By placing the notched structure so that its straight sides become parallel to the waveguide that is 250 nm away, the results mentioned above can be used to determine coupling length. 108.20 $\mu$m is the length for which both polarizations are transferred to the notched structure. The notch has a width and height of 175 nm, as shown in figure 3(b), and is used to provide an interchange of energy between horizontal and vertical polarization modes. Different angles of half-wave plates can be implemented by manipulating the notch size of the structure. Figure 4 shows the change in the quantity of horizontal and vertical polarizations at the output port with respect to notch size.

For HWP1, by considering pure vertical polarization, since horizontal polarization is not expected to reach HWP1, the notch size is decided to be 0.75 $\mu$m to 1/4 of output energy belonging to horizontal polarization mode, while the rest stays in vertical polarization mode. Note that there is polarization-dependent loss that is turned into polarization-independent loss by choosing notch length such a way that desired portion of each polarization will outcome. The loss for this case is $-0.56$ dB. On the other hand, for HWP2 and HWP3, input has horizontal and vertical components and different notch lengths should be used for different input polarizations. It can be achieved by splitting two polarization components and then sending them to different notched ring resonators. The structure shown in figure 5 is suitable for this purpose. From our previous coupling calculations,
the length of the initial directional coupler (DC) is 70.72 μm. The notch length of the ring resonator in the upper arm (NRR₁), where horizontal polarization is processed, should be 2.90 μm, while that of the ring resonator in the lower arm (NRR₂) should be 2.75 μm. In both cases, the output of notched ring resonators consists of equal energy of horizontal and vertical polarization states. The overall loss for this structure is −0.66 dB. All wave distributions for both polarizations and three notch lengths mentioned above are shown in figure 6.

We also perform simulations with slightly different dimensions to ensure the feasibility of fabricating such an integrated circuit. Figure 7 shows the 1 μm coupler response to alteration of the waveguide height, width, and distance between two waveguides. For all cases, the deviation from desired outcome, which means deviation of
energy inside the waveguide from ideal case, becomes less than 20%. Similarly, deviations from desired outcomes of notched ring resonators to the changes in notch height & width, waveguide height & waveguide width are shown in figure 8. Even though the $+/-10 \text{ nm}$ sensitivity characteristics look challenging, today’s fabrication techniques enable us to produce waveguides with precision in such a range $[42, 43]$. Some experimental analyses of fabrication faults of less than 10 nm at integrated photonic elements are also available in literature $[44, 45]$.

Defects emerged during fabrication is another common problem for photonic integrated circuits. We simulate directional couplers with defects to examine their effect. We consider deviation of energy after light propagates through 5 $\mu$m inside the coupler with randomly distributed 1, 5 and 10 defects with sizes ranging from 0.01 $\mu$m to 0.20 $\mu$m. For 1 defect, the general loss is 0.68% and change of the distribution between two waveguides is as small as 0.03%. For 5 defects, general loss is 6.71% and change of the distribution between two waveguides becomes 0.60%. For 10 defects, general loss is 16.82% and the distribution change becomes 1.64%. The unwanted polarization conversion as a result of defects becomes 3.26% for this last case.

Lastly, possible ways of utilization of this gate in cascaded circuits should be examined to complete the analysis. Because success of the gate, i.e. adding phase to target photon if both target and control qubits are $|1\rangle$ and outputting two photons without phase difference otherwise, depends not only on detection of a photon at detector but also outputting exactly one photon from each of the target and control outputs, it is more challenging to decide successful operation of a circuit composed of this gate. In other words, if existence of photons can’t be determined precisely without harming quantum information encoded on them, there will be
no way to decide whether an operation becomes successful or not. We propose some ways to tackle this problem. First of all, in literature there are methods named nondestructive [46, 47] or non-demolition [48, 49] measurements which can be used to measure photon existence without destroying it (figure 9). Instead of using these methods, it is also possible to employ the gate in a specific way to indirectly control its outputs, such as designing the overall circuit such a way that control and target outputs will be processed separately after the gate, or using the gate as last element of the circuit, right before the detectors.

3. Conclusion

In conclusion, we proposed an integrated programmable controlled phase gate for quantum information processing. As a polarization rotator, we used a unique notched ring resonator that can be practically fabricated and is compatible with rectangular waveguide circuits. All of the elements proposed above can be feasibly fabricated thanks to the techniques such as deep ultraviolet lithography or e-beam lithography [50–52]. Moreover, it is possible to use some auto-configuration techniques to compensate effect of imperfections at interferometers [53]. In this case, the extinction ratio becomes 60 dB, which leads to less than 0.1% of loss for whole of our circuit. The success probability of the gate for ideal components is 1/48, which is less than KLM result of 2/27 for controlled-Z gate. However, our gate has a unique property of determining phase difference during the operation, which provides extra advantage over conventional gates. It should also be mentioned that the success probability can be increased to 1/12 by adding a feed-forward phase modulation for certain usage of the gate [35]. Our compact integrated design of this gate will pave the way for large-scale quantum information processing by providing the opportunity for more versatile quantum operations.

Acknowledgments

We thank Emre Yüce for many fruitful discussions on the topic. Y B thankfully acknowledges financial support from the Council of Higher Education (YÖK) under the 100/2000 Doctorate Project and the Scientific and Technological Research Council of Turkey (TÜBİTAK) under the 2211-A General Domestic Doctorate Scholarship Program. Authors are grateful for the support from the Turkish Academy of Sciences Outstanding Young Scientists Awards (GEBİP).

Data availability statement

The data cannot be made publicly available upon publication because the cost of preparing, depositing and hosting the data would be prohibitive within the terms of this research project. The data that support the findings of this study are available upon reasonable request from the authors.

ORCID iDs

Yalın Başay © https://orcid.org/0000-0001-7313-6513
Serdar Kocaman © https://orcid.org/0000-0003-4850-7209

References

[1] Arute F et al 2019 Quantum supremacy using a programmable superconducting processor Nature 574 505–10
[2] Zhong H-S et al 2020 Quantum computational advantage using photons Science 370 1460–3
[3] Harrow A W and Montanaro A 2017 Quantum computational supremacy Nature 549 203–9
[4] Barreiro J T, Müller M, Schindler P, Nigg D, Monz T, Chwalla M, Hennrich M, Roos C F, Zoller P and Blatt R 2011 An open-system quantum simulator with trapped ions Nature 470 486–91
Saber Md G, Abadía N and Plant D V 2018 CMOS compatible all-silicon TM pass polarizer based on highly doped silicon waveguide

Marcikic I, de Riedmatten H, Tittel W, Zbinden H, Legré M and Gisin N 2004 Distribution of time-bin entangled qubits over 50 km of fiber

Wang S M, Cheng Q Q, Gong Y X, Xu P, Sun C, Li L, Li T and Zhu S N 2016 A 14

Xu X B, Shi L, Guo G C, Dong C H and Zou C L 2019

Politi A, Cryan M J, Rarity J G, Yu S and O’ Brien J L 2008 silica-on-silicon waveguide quantum circuits Science (1979) 320 666–9

Kupchak C, Bustard P J, Heshami K, Erskine J, Spanner M, England C and Sussman B J 2017 Time-bin-to-polarization conversion of single-photon states in silicon

Bozkurt A B and Kocaman S 2021 Linear optical deterministic and recon-figurable SWAP Gate

Humphreys P C, Metcalf B J, Spring J B, Moore M, Jin X M, Barbieri M, Kolthammer W S and Walmsley I A 2013 Linear optical quantum computing in a single spatial mode Phys. Rev. Lett. 111 1–5

Erhard M, Fickler R, Krenn M and Zeilinger A 2018 Twisted photons: new quantum perspectives in high dimensions light Science and Applications 7 17146

Marcikic I, de Riedmatten H, Tittel W, Zbinden H, Legré M and Gisin N 2004 Distribution of time-bin entangled qubits over 50 km of optical fiber Phys. Rev. Lett. 93 1–4

Kupchak C, Bickel P J, Heshami K, Erskine J, Spanner M, England C and Sussman B J 2017 Time-bin-to-polarization conversion of ultrafast photonics Phys. Rev. A 96 1–5

Lo H P, Ikuta T, Matsuda N, Honjo T, Munro W J and Takesue H 2020 Quantum process tomography of a controlled-phase gate for time-bin qubits Physical Review Applied 13 034013

Kaiser F, Aktas D, Pedrici B, Lunghi T, Labonte L and Tannizzi S 2016 Optimal analysis of ultra broadband energy-time entanglement for high bit-rate dense wavelength division multiplexed quantum networks Appl. Phys. Lett. 108 231108

Andriano S N, Kalachev A A and Shindyavev O P 2018 Controlled-NOT gate for frequency-encoded qubits based on six-wave mixing Laser Phys. 28 125204

Schaeff C, Polster R, Lapkiewicz R, Fickler R, Ramelow S and Zeilinger A 2012 Scalable fiber integrated source for higher-dimensional path-entangled photon qubits Opt. Express 20 16145

Wang J et al 2016 Chip-to-chip quantum photonic interconnect by path-polarization interconversion Optica 3 407

Bergamasco N, Menotti M, Sipe J E and Liscidini M 2017 Generation of path-encoded greenberger-horne-zeilinger states Physical Review Applied 8 1–8

Bunandar D et al 2018 Metropolitan quantum key distribution with silicon photonics Physical Review X 8 21009

Roger T, de Marco I, Paraske V, Marangon D, Yuan Z and Shields A 2019 Real-time interferometric quantum random number generation on chip CLEO 2019 - Proceedings B13 37–42

Caruso F, Crespi A, Ciriolo G, Sciarrino F and Oeslame R 2016 Fast escape of a quantum walker from an integrated photonic maze Nature Communications 7 1–7

Wang J et al 2017 Experimental quantum hamiltonian learning Nature Physics (N.Y.) 13 551–5

Scott R E, Alsing P M, Smith A M, Fano M L, Tison C G, Schneeloch J and Hach E F 2019 Scalable controlled-not gate for linear optical quantum computing using microring resonators Phys. Rev. A 100 022322

Li M, Zhang Q, Gong Q and Li Y 2019 Integrated path-encoded CNOT quantum gate fabricated by femtosecond laser direct writing Frontiers in Optics - Proceedings Frontiers in Optics + Laser Science APS/DLS 2018 23 18–21

Bozkurt A B and Kocaman S 2019 On-chip deterministic optical SWAP gate quantum Nanophotonic Materials, Devices, and Systems ed M Afgio et al (San Diego, California, United States: SPIE) 2019, 32 1109110

Cheng X et al 2020 An Efficient On-chip Single-photon SWAP Gate for Entanglement Manipulation Conference on Lasers and Electro-Optics (Washington DC, United States: OSA) F7A28 5

Bozkurt A B and Kocaman S 2021 Linear optical deterministic and reconfigureable SWAP Gate Quantum Inf. Process. 21 1–12

Humphreys P C, Metcalf B J, Spring J B, Moore M, Jin X M, Barbieri M, Kolthammer W S and Walmsley I A 2013 Linear optical quantum computing in a single spatial mode Phys. Rev. Lett. 111 1–5

Kang Y H, Xia Y and Lu P M 2014 Efficient and flexible protocol for implementing two-qubit controlled phase gates with cross-Kerr nonlinearity J. Mod. Opt. 61 75–81

Lemr K, Bartkiewicz K and Černoch A 2015 Scheme for a linear–optical controlled–phase gate with programmable phase shift Journal of Optics (United Kingdom) 17 125202

Wang J, Sciarrino F, Laing A and Thompson M G 2020 Integrated photonic quantum technologies Nat. Photonics 14 273–84

Politi A, Cryan M J, Rarity J G, Yu S and O’Brien J L 2008 silica-on-silicon waveguide quantum circuits Science (1979) 320 666–9

Crespi A, Ramponi R, Oeslame R, Sansoni L, Bongioanni I, Sciarrino F, Vallone G and Mataloni P 2011 Integrated photonic quantum gates for polarization qubits Nat. Commun. 2 566

Kieling K, O’Brien J L and Eisert J 2010 On photonic controlled phase gates New J. Phys. 12 013003

Xu X B, Shi L, Guo G C, Dong C H and Zou C L 2019 ‘Mobius’ microring resonator Appl. Phys. Lett. 114 101106

Oskooi A F, Roundy D, Ibanescu M, Bermel F, Joannopoulos J D and Johnson S G 2010 Meep: a flexible free-software package for electromagnetic simulations by the FDTD method Comput. Phys. Commun. 181 687–702

Xu J D, Schmidt H J, Reed G T, Mashanovich G Z, Thomson D J, Nedeljkovic M, Chen X, van Thourhout D, Keyvaninia S and Selvaraja S K 2014 silicon photonic integration platform—Have we found the sweet spot? IEEE J. Sel. Top. Quantum Electron. 20 189–205

Saber Md G, Abadía N and Plant D V 2018 CMOS compatible all-silicon TM pass polarizer based on highly doped silicon waveguide Opt. Express 26 20878–87

Mirza A, Sunny F, Pasricha S and Nikolast M 2020 Silicon photonics microring resonators: design optimization under fabrication non-uniformity 2020 Design, Automation & Test in Europe Conference & Exhibition (DATE) (Grenoble, France, 09–13 March 2020) (https://doi.org/10.23919/DATE48585.2020.9116201)

Xing Y, Dong J, Khan U and Bogaerts W 2023 Capturing the effects of spatial process variations in silicon photonic circuits ACS Photonics 10 928–44
[46] Reiserer A, Ritter S and Rempe G 2013 Nondestructive Detection of an Optical Photon Science 342 1349–51
[47] Niemietz D, Ferrera P, Langenfeld S and Rempe G 2021 Nondestructive detection of photonic qubits Nature 591 570–4
[48] Balybin S N, Matsko A B, Khalili F Y, Strekalov D V, Ilchenko V S, Savchenkov A A, Lebedev N M and Bilenko I A 2022 Quantum nondemolition measurements of photon number in monolithic microcavities Phys Rev A (Coll Park) 106 013720
[49] Chen S Y, Chen L Q, Ou Z Y and Hang W 2017 Quantum non-demolition measurement of photon number with atom–light interferometers Opt. Express 25 31827
[50] Chen G F R, Ong J R, Ang T Y L, Lim S T, Png C E and Tan D T H 2017 Broadband Silicon–On–Insulator directional couplers using a combination of straight and curved waveguide sections Sci. Rep. 7 4–11
[51] Zhao N, Qiu C, He Y, Zhang Y and Su Y 2019 Broadband polarization beam splitter by using cascaded tapered bent directional couplers IEEE Photonics Journal 11 1–8
[52] Su Y, Zhang Y, Qiu C, Guo X and Sun L 2020 Silicon photonic platform for passive waveguide devices: materials, fabrication, and applications Advanced Materials Technologies 5 1–19
[53] Wilkes C M, Qiang X, Wang J, Santagati R, Paesani S, Zhou X, Miller D A B, Marshall G D, Thompson M G and O’Brien J L 2016 60 dB high-extinction auto-configured Mach–Zehnder interferometer Opt. Lett. 41 5318