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Scheme for implementing linear optical quantum iSWAP gate with conventional photon detectors

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A simple scheme is proposed to implement two-qubit linear optical quantum iSWAP gate that is a universal gate in quantum computation and quantum information processing. By the interference effect of the polarized photons, a quantum iSWAP gate can be achieved with a low success probability ($\frac{\eta^4}{32}$, with η being the quantum efficiency of photon detectors). The scheme is based only on simple linear optical elements, a pair of two-photon polarization entangled states, and conventional photon detectors that only distinguish the vacuum and nonvacuum Fock number states, which greatly decreases the experimental difficulty of implementing linear optical quantum computation.

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Quantum computers, which are based on fundamental quantum mechanical superposition principle, have been attracting more and more interests since they are considered to be capable of tackling efficiently certain problems that are intractable for classical computers, such as factoring problem [1], search problem [2], counting solution problem [3], phase estimation problem [4], hidden subgroup problem [5,6], etc.. The essential building blocks of a quantum computer are quantum logical gates, which have received a lot of attention. It has been shown that any quantum logical operation in quantum computation can be implemented only with one-qubit unitary gates and two-qubit conditional gates, such as controlled phase flip (CPF) gate and controlled-NOT (CNOT) gate. In this sense, a set of these elementary gates is universal for quantum computation and building quantum computer. Many schemes [7–14] have been proposed to implement CPF gate and CNOT gate in both theoretical and experimental aspects.

Recently, a notable two-qubit quantum logical gage, iSWAP gate, was proposed for one-way quantum computation and constructing multi-qubit logical gates [15–17]. The iSWAP gate is a universal gate in quantum computation and can be naturally generated from solid-state interqubit interaction described by XY-type exchange Hamiltonian [18]. The iSWAP gate transforms the states as

$$|00\rangle_{12} \rightarrow |00\rangle_{12}, \quad |01\rangle_{12} \rightarrow i|10\rangle_{12}, \quad |10\rangle_{12} \rightarrow i|01\rangle_{12}, \quad |11\rangle_{12} \rightarrow |11\rangle_{12}. \tag{1}$$

Schuch and Siewert [15] have shown that several quantum logical gates, such as two-qubit CPF and CNOT gates, could be easily synthesized by using iSWAP gate, together with several one-qubit rotation gates. Particularly, they illustrated that the complicated CNS gate (see Fig. 1(a)) that combines CNOT with the SWAP gate operations could be simply implemented by applying iSWAP gate only once, which was a significant simplification for quantum computation. Tanamoto *et al.* [16] have proposed efficient schemes for entanglement purification in solid-state qubits by replacing the usual bilateral CNOT gate by the bilateral iSWAP gate. Tanamoto *et al.* [17] have proposed an efficient way for the generation of multi-qubit cluster state in higher dimensions and illustrated that distant qubits can be connected with iSWAP gate. Enlightened by above works, in this paper, we propose a simple linear optical scheme to implement two-qubit iSWAP gate with a low success probability by the interference effect of the polarized photons. The proposed setup consists of simple linear optical elements, a pair of two-photon polarization entangled states, and conventional photon detectors. In contrast to sophisticated single-photon detectors distinguishing one or two photon states, the conventional photon detectors cannot distinguish a single photon from two or more photons and can only distinguish the vacuum and nonvacuum Fock number states. This greatly decreases the high-quality requirements of photon detectors and makes the scheme more feasible in experiments.

To implement the linear optical quantum iSWAP gate, we first describe the quantum encoder circuit proposed in Refs. [11,12], as shown in Fig. 1(b). It consists of one 22.5°-tilted half-wave plate (HWP) $R_{22.5}$ (the title angle means the angle between the axis of the HWP and the horizontal direction), two polarization beam splitters (PBS), and two photon detectors D_5 and D_6. The action of $R_{22.5}$ is given by

$$|H\rangle \rightarrow \frac{1}{\sqrt{2}}(|H\rangle + |V\rangle),$$

$$|V\rangle \rightarrow \frac{1}{\sqrt{2}}(|H\rangle - |V\rangle), \tag{2}$$

which represents Hadamard gate transformation (H transformation). Here $|H\rangle$ ($|V\rangle$) denotes the horizontal (vertical) polarization state of a photon, and $|H\rangle$ and $|V\rangle$ correspond the logical zero and one states, respectively, $|0\rangle \equiv |H\rangle$ and $|1\rangle \equiv |V\rangle$. The action of the polarization beam splitter is to split randomly polarized beams into two orthogonal, linearly polarized components: V-polarized light is reflected at a 90 degree angle while H-polarized light is transmitted. For example, in Fig. 1(c), assume that the input photon is in state $|\phi\rangle_{in} = a|H\rangle_0 + b|V\rangle_0$. After the PBS, we obtain $|\phi\rangle_{out} = a|H\rangle_1 + b|V\rangle_2$. Polarization beam splitters come in cube form, but custom geometries are available. Usually, the principal transmittance of the polarization beam splitter, $T_H > 95\%$, $T_V < 1\%$; and the principal reflectance, $R_V > 98\%$, $R_H < 1\%$. Here, T and R denote the transmittance and reflectance, respectively. If the photons pass through the PBS away from the principal axis of the PBS, the transmittance and reflectance will be decreased, leading to the unstable interference of the polarized photons. Therefore, the success probability and the fidelity of the gate operation will be affected. Suppose that mode 1, which carries the state to be encoded, is prepared in state $|\psi\rangle_{\text{in}} = \alpha|H\rangle_1 + \beta|V\rangle_1$, with α and β being complex coefficients satisfying $|\alpha|^2 + |\beta|^2 = 1$. Modes 2 and 3 of the encoder circuit shown in Fig. 1(b) are prepared in a two-photon polarization entangled state: $|\psi\rangle_{23} = (|H\rangle_2|H\rangle_3 + |V\rangle_2|V\rangle_3)/\sqrt{2}$. Let modes 1 and 2 be mixed at the PBS_1 in the quantum encoder circuit. After passing through a series of linear optical elements, the resulting state of the system becomes

$$\frac{1}{\sqrt{2}}(\alpha|H\rangle_1 + \beta|V\rangle_1)(|H\rangle_2|H\rangle_3 + |V\rangle_2|V\rangle_3)$$

$$\rightarrow \frac{1}{2}[|H\rangle_5(\alpha|H\rangle_{2'}|H\rangle_3 + \beta|V\rangle_{2'}|V\rangle_3) \ + |V\rangle_6(\alpha|H\rangle_{2'}|H\rangle_3$$

$$-\beta|V\rangle_{2'}|V\rangle_3)] + \frac{1}{\sqrt{2}}\alpha|HV\rangle_{2'}|V\rangle_3 + \frac{1}{2}\beta(|2H\rangle_5 - |2V\rangle_6)|H\rangle_3. \quad (3)$$

The photons in modes 5 and 6 are detected by conventional photon detectors D_5 and D_6. The character of a conventional photon detector is that it cannot distinguish a single photon from two or more photons and can only distinguish between the presence and absence of photons. The expression of the positive-operator-valued-measure (POVM) elements for a conventional photon detector with a quantum efficiency η is written as [12, 19]

$$\Pi_{c0} = \sum_{m=0}^{\infty}(1-\eta)^m|m\rangle\langle m|,$$

$$\Pi_{c1} = 1 - \Pi_{c0} = \sum_{m=0}^{\infty}[1-(1-\eta)^m]|m\rangle\langle m|, \quad (4)$$

where Π_{c0} is the POVM element for no photocounts and Π_{c1} is that for photocounts. After the detection, we obtain the following transformation [11, 12]

$$\alpha|H\rangle_1 + \beta|V\rangle_1 \rightarrow \alpha|H\rangle_{2'}|H\rangle_3 + \beta|V\rangle_{2'}|V\rangle_3, \quad (5)$$

which represents the quantum encoding transformation of the setup shown in Fig. 1(b). The success probability is $P_e = \eta/2$.

In the following we show how to implement quantum iSWAP gate by using quantum encoding transformation (5) and conventional photon detectors. The schematic representation of the scheme is shown in Fig. 2. We consider an arbitrary two-photon input state written as

$$\alpha_1|H\rangle_{a_1}|H\rangle_{a_2} + \alpha_2|H\rangle_{a_1}|V\rangle_{a_2} + \alpha_3|V\rangle_{a_1}|H\rangle_{a_2} + \alpha_4|V\rangle_{a_1}|V\rangle_{a_2}, \quad (6)$$

where α_i is an arbitrary complex number satisfying normalization condition $\sum_{i=1}^{4}|\alpha_i|^2 = 1$. As shown in Fig. 2, we first apply the encoding transformations F to encode photons a_1 and a_2. After that, the state of the system is given by

$$\alpha_1|H\rangle_{b_1}|H\rangle_{b_2}|H\rangle_{b_3}|H\rangle_{b_4} + \alpha_2|H\rangle_{b_1}|H\rangle_{b_2}|V\rangle_{b_3}|V\rangle_{b_4}$$

$$+\alpha_3|V\rangle_{b_1}|V\rangle_{b_2}|H\rangle_{b_3}|H\rangle_{b_4}+\alpha_4|V\rangle_{b_1}|V\rangle_{b_2}|V\rangle_{b_3}|V\rangle_{b_4}, \tag{7}$$

with the success probability $P_{e'}=\eta^2/4$. Let the photons in modes b_j $(j=2,3)$ pass through the phase modulator PM_k $(k=1,2)$, whose action is given by the transformation $|H\rangle_{b_j}\rightarrow|H\rangle_{b_j}$ and $|V\rangle_{b_j}\rightarrow e^{i\phi}|V\rangle_{b_j}$, and the photon in mode b_4 passes through a HWP $\mathrm{R}_{22.5}$. The state (7) becomes

$$\frac{1}{\sqrt{2}}\big[\alpha_1|H\rangle_{b_1}|H\rangle_{b_2'}|H\rangle_{b_3'}(|H\rangle_{b_4'}+|V\rangle_{b_4'})+\alpha_2e^{i\phi}|H\rangle_{b_1}|H\rangle_{b_2'}|V\rangle_{b_3'}(|H\rangle_{b_4'}-|V\rangle_{b_4'})$$

$$+\alpha_3e^{i\phi}|V\rangle_{b_1}|V\rangle_{b_2'}|H\rangle_{b_3'}(|H\rangle_{b_4'}+|V\rangle_{b_4'})+\alpha_4e^{i2\phi}|V\rangle_{b_1}|V\rangle_{b_2'}|V\rangle_{b_3'}(|H\rangle_{b_4'}-|V\rangle_{b_4'})\big]. \tag{8}$$

Let the photons in modes b_2' and b_3' pass through PBS_1 and PBS_2, and let modes b_1 and b_4' be mixed at PBS_3, giving

$$\frac{1}{\sqrt{2}}\big[\alpha_1|H\rangle_{b_{10}}|H\rangle_{b_5}|H\rangle_{b_8}(|H\rangle_{b_9}+|V\rangle_{b_{10}})+\alpha_2e^{i\phi}|H\rangle_{b_{10}}|H\rangle_{b_5}|V\rangle_{b_7}(|H\rangle_{b_9}-|V\rangle_{b_{10}})$$

$$+\alpha_3e^{i\phi}|V\rangle_{b_9}|V\rangle_{b_6}|H\rangle_{b_8}(|H\rangle_{b_9}+|V\rangle_{b_{10}})+\alpha_4e^{i2\phi}|V\rangle_{b_9}|V\rangle_{b_6}|V\rangle_{b_7}(|H\rangle_{b_9}-|V\rangle_{b_{10}})\big]. \tag{9}$$

The photons in modes b_5, b_6, b_7, and b_8 are rotated by the HWPs R_{45}, whose action is given by $|H\rangle\leftrightarrow|V\rangle$. After that, as shown in Fig. 2, let modes b_6' and b_7' be mixed at PBS_4, and modes b_5' and b_8' be mixed at PBS_5. The state of the system is written as

$$\frac{1}{\sqrt{2}}\big[\alpha_1|H\rangle_{b_{10}}|V\rangle_{c_3}|V\rangle_{c_4}(|H\rangle_{b_9}+|V\rangle_{b_{10}})+\alpha_2e^{i\phi}|H\rangle_{b_{10}}|V\rangle_{c_3}|H\rangle_{c_1}(|H\rangle_{b_9}-|V\rangle_{b_{10}})$$

$$+\alpha_3e^{i\phi}|V\rangle_{b_9}|H\rangle_{c_2}|V\rangle_{c_4}(|H\rangle_{b_9}+|V\rangle_{b_{10}})+\alpha_4e^{i2\phi}|V\rangle_{b_9}|H\rangle_{c_2}|H\rangle_{c_1}(|H\rangle_{b_9}-|V\rangle_{b_{10}})\big]. \tag{10}$$

The photons in modes b_9, b_{10}, c_3, and c_4 are sent through the HWPs $\mathrm{R}_{22.5}$, and the photons in modes c_1 and c_2 are sent through the HWPs $\mathrm{R}_{67.5}$, whose action is given by the transformation

$$|H\rangle\rightarrow\frac{1}{\sqrt{2}}(|V\rangle-|H\rangle),$$

$$|V\rangle\rightarrow\frac{1}{\sqrt{2}}(|V\rangle+|H\rangle). \tag{11}$$

After the photons in modes d_l ($l = 1, 2, \ldots, 6$) pass through PBS_m ($m = 6, 7, 8, 9$), the state of the system is given by

$$\frac{1}{4\sqrt{2}}\big\{\alpha_1(|H\rangle_{e_6}+|V\rangle_{e_5})(|H\rangle_{e_2}-|V\rangle_{e_2'})(|H\rangle_{e_1}-|V\rangle_{e_1'})[(|H\rangle_{e_3}+|V\rangle_{e_4})$$

$$+(|H\rangle_{e_6}-|V\rangle_{e_5})]+\alpha_2 e^{i\phi}(|H\rangle_{e_6}+|V\rangle_{e_5})(|H\rangle_{e_2}-|V\rangle_{e_2'})(|V\rangle_{e_1}-|H\rangle_{e_1'})$$

$$\otimes[(|H\rangle_{e_3}+|V\rangle_{e_4})-(|H\rangle_{e_6}-|V\rangle_{e_5})]+\alpha_3 e^{i\phi}(|H\rangle_{e_3}-|V\rangle_{e_4})(|V\rangle_{e_2}-|H\rangle_{e_2'})$$

$$\otimes(|H\rangle_{e_1}-|V\rangle_{e_1'})[(|H\rangle_{e_3}+|V\rangle_{e_4})+(|H\rangle_{e_6}-|V\rangle_{e_5})]+\alpha_4 e^{i2\phi}(|H\rangle_{e_3}-|V\rangle_{e_4})$$

$$\otimes(|V\rangle_{e_2}-|H\rangle_{e_2'})(|V\rangle_{e_1}-|H\rangle_{e_1'})[(|H\rangle_{e_3}+|V\rangle_{e_4})-(|H\rangle_{e_6}-|V\rangle_{e_5})]\big\}. \tag{12}$$

We only consider the events that there exist photons in one of the detectors D_{e_3} and D_{e_4} and one of the detectors D_{e_5} and D_{e_6}. If photon detectors D_{e_3} and D_{e_6} (D_{e_4} and D_{e_5}) detect photons and the others do not register any photon, the state of modes e_1 and e_2 is given by

$$\alpha_1|H\rangle_{e_1}|H\rangle_{e_2}+\alpha_2 e^{i\phi}|V\rangle_{e_1}|H\rangle_{e_2}+\alpha_3 e^{i\phi}|H\rangle_{e_1}|V\rangle_{e_2}-\alpha_4 e^{i2\phi}|V\rangle_{e_1}|V\rangle_{e_2}, \tag{13}$$

with the success probability $P_o = \eta^2/16$. If photon detectors D_{e_3} and D_{e_5} (D_{e_4} and D_{e_6}) detect photons and the others do not register any photon, the state of modes e_1 and e_2 is given by

$$\alpha_1|H\rangle_{e_1}|H\rangle_{e_2}+\alpha_2 e^{i\phi}|V\rangle_{e_1}|H\rangle_{e_2}-\alpha_3 e^{i\phi}|H\rangle_{e_1}|V\rangle_{e_2}+\alpha_4 e^{i2\phi}|V\rangle_{e_1}|V\rangle_{e_2}, \tag{14}$$

which can be transformed into state (13) by applying a $\pi/2$-phase modulator PM to change the sign of the polarization state $|V\rangle_{e_2}$. With the choice of $\phi = \pi/2$, the state (13) becomes

$$\alpha_1|H\rangle_{e_1}|H\rangle_{e_2}+i\alpha_2|V\rangle_{e_1}|H\rangle_{e_2}+i\alpha_3|H\rangle_{e_1}|V\rangle_{e_2}+\alpha_4|V\rangle_{e_1}|V\rangle_{e_2}. \tag{15}$$

Therefore, we implement a two-qubit linear optical quantum iSWAP gate. The total success probability is

$$P = 2P_{e'}P_o = \frac{\eta^4}{32}, \tag{16}$$

which was plotted in Fig. 3 as a function of η.

In conclusion, we have proposed a linear optical scheme for the implementation of two-qubit quantum iSWAP gate with conventional photon detectors. The scheme has the following merits: (i) it does not require the optical paths to be stable to subwavelength order; (ii) during the process of detection, we only need to use the conventional photon detectors that only distinguish the vacuum and nonvacuum Fock number states. A sophisticated single-photon detector distinguishing one or two photon states is unnecessary. Therefore, our scheme greatly decreases the high-quality requirements of photon detectors in practical realization [20]; (iii) photons are ideal carriers for transmitting quantum information over long distances; (iv) the fast polarization modulation is unnecessary. Furthermore, one can see from the proposed scheme that it is possible to have probabilistic iSWAP gates with linear optical elements and conventional photon detectors that do not distinguish between single-photon and multiple-photon events. In the meantime, how to find more efficient schemes for practical use is very important and necessary. On the other hand, as resources, experimental realization of our scheme requires the consumption of entangled photon pairs. Therefore, we require reliable sources of single photons to serve as the qubits of interest, as well as reliable sources of deterministic entangled photon pairs to serve as the ancilla. Experimentally, various schemes have been proposed to produce single photons [21–26] and a triggered source of two-photon entangled states can be generated using recently developed quantum-dot techniques [27, 28]. Therefore, our scheme might be experimentally feasible with the presently available techniques.

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Fig. 1. (a) Quantum circuit for implementing CNS gate that is a combination of CNOT and SWAP gates by using iSWAP gate and one-qubit rotation gates. Here H denotes Hadamard gate transformation, and $R_z^\theta = e^{-i\theta\sigma_z/2}$. (b) Schematic diagram for the quantum encoder circuit. PBS_i $(i = 1, 2)$ denotes polarization splitter, which transmits the horizontal polarization and reflects vertical polarization. $\mathrm{R}_{22.5}$ denotes 22.5°-tilted HWP, and $\mathrm{D}_{5(6)}$ are detectors. (c) Schematic diagram for the action of the PBS.

Fig. 2. Schematic setup of implementing two-qubit linear optical quantum iSWAP gate. F denotes the encoding transformation shown in Fig. 1(b), R_{45} denotes 45°-tilted HWP, $\mathrm{R}_{67.5}$ denotes 67.5°-tilted HWP, and PM_i $(i = 1, 2)$ are phase modulators.

Fig. 3. The total success probability for implementing two-qubit linear optical quantum iSWAP gate, P vs. η.

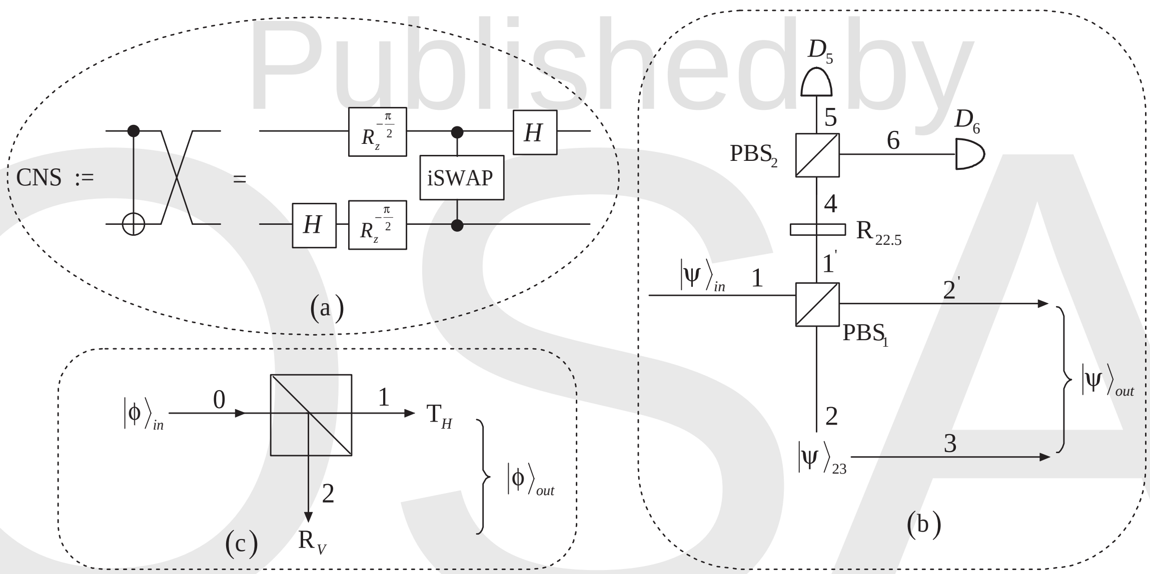
CNS :=
=
H
iSWAP
(a)
D5
D6
5
6
PBS2
4
R22.5
1'
|ψ⟩in
1
2'
PBS1
|ψ⟩out
2
|ψ⟩23
3
(b)
|φ⟩in
0
1
TH
2
RV
|φ⟩out
(c)

Fig. 1.

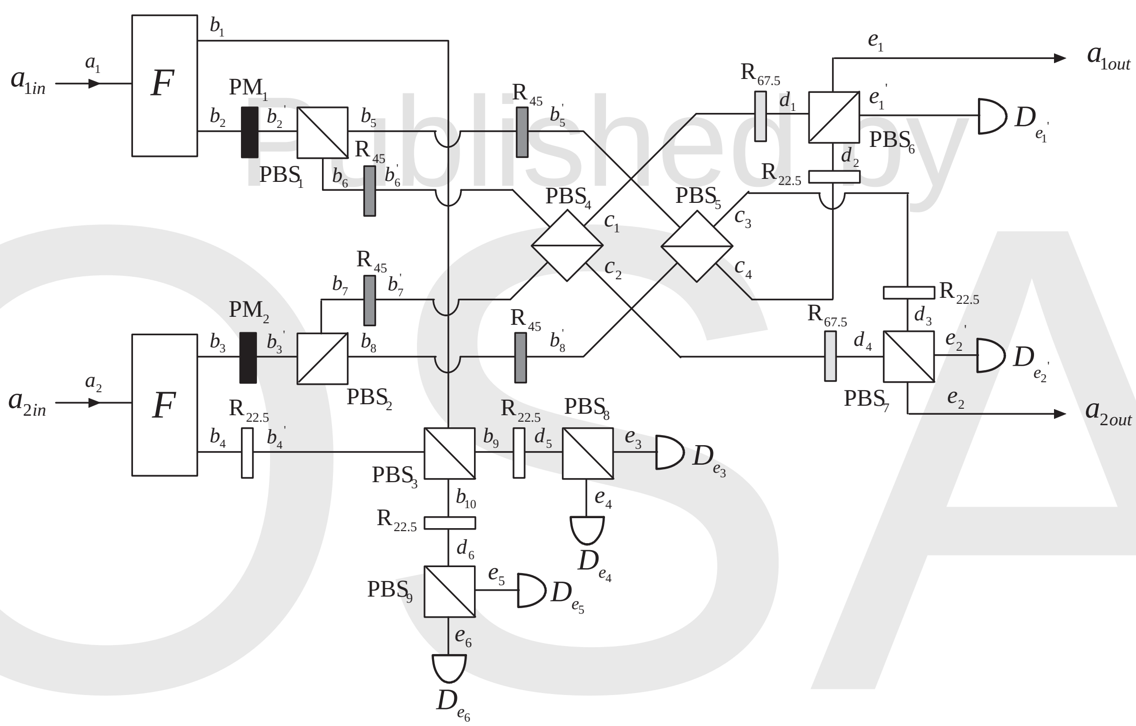
a1in
a1
F
b1
b2
PM1
b2'
PBS1
b5
b6
R45
b6'
R45
b5'
PBS4
PBS5
c1
c2
c3
c4
R67.5
d1
e1
e1'
PBS6
De1'
a1out
R22.5
d2
R22.5
d3
R67.5
d4
e2'
De2'
PBS7
e2
a2out
b7
R45
b7'
PM2
b3
b3'
b8
R45
b8'
PBS2
a2in
a2
F
R22.5
b4
b4'
PBS3
b9
R22.5
d5
PBS8
e3
De3
e4
De4
b10
R22.5
d6
PBS9
e5
De5
e6
De6

Fig. 2.

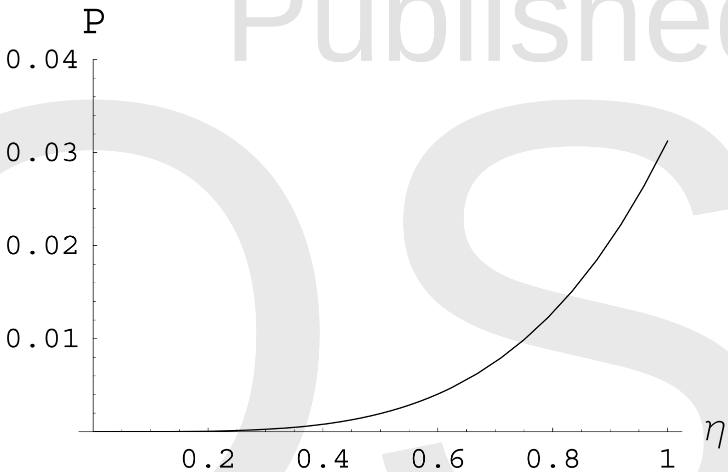

Fig. 3.