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Implementation of quantum optical tristate oscillators based on tristate Pauli-X, Y and Z gates by using joint encoding of phase and intensity

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Oscillator circuit has the significant role to always repeat the same signal at the output after certain time interval. In quantum computing, intensity and phase of light signal can be made oscillatory at the output of a quantum optical oscillator circuit. In this paper, we have implemented quantum optical tristate oscillator circuits based on tristate Pauli-X, Y and Z gates using phase and intensity encoding technique of light signal. Here, three different oscillator circuits are developed. The phase of light signal is chosen as the oscillating parameter in all proposed circuits. The truth tables and oscillating phase diagrams are also shown for each oscillator circuit in this paper. The operation of one of the oscillator circuits is simulated with MATLAB to prove its feasibility.
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An oscillator circuit repeats the same output at a certain time interval even after removing the external input signal. In quantum optical circuits, quantized parameters of light are used as signal carriers[1,2]. So, the possible oscillating parameters of light are its intensity, phase, etc. The oscillator circuit with oscillating intensity has been proposed earlier[3]. In this communication, authors have developed optical tristate oscillator circuits based on tristate Pauli-X, Y and Z quantum logic gates. Tristate Pauli-X, Y and Z quantum logic gates have already been proposed[4]. These gates are used here to design tristate oscillator circuits. Only the phase of the light signal is chosen as the oscillating parameter. Therefore, phase encoding technique[5-11] is primarily used to design these oscillator circuits. Electro-optic modulators (EOMs) are used to change the phase of the light signal to a desired value[5-13]. The intensity of light is also encoded here along with the phase which is referred as the joint encoding of phase and intensity. The zero (0) state is the indication of absence of light (no intensity) and any non-zero state represents the presence of light intensity. Any state 1 represents the state of light with a specific intensity (I) and zero phase difference. Similarly, −1, i, and −i states are the states with a specific intensity (I) and with phase differences by π, $\frac{\pi}{2}$ and $-\frac{\pi}{2}$ respectively with respect to initial inputs. C_0, C_1 and C_2 are the generalized form of the states. These states can be any of 1, −1, i, −i, etc. Erbium doped fiber amplifiers (EDFAs) can be used to maintain the intensity of light through the channels[12-14]. Separate oscillator circuits are developed for each of tristate Pauli-X, Y and Z gates respectively and the MATLAB simulation results for one of the circuits are shown. The tristate form of the circuits provides high degree of parallelism[15,16].

Tristate Pauli-X gate has only one circuit, but tristate Pauli-Y and Z gates have four and two different circuits respectively[4]. Only one circuit from each of Pauli-X, Y and Z gates is used to design three different tristate oscillator circuits. Fig.1 shows the circuit diagrams for tristate Pauli-X, Y and Z gates individually which are used to implement oscillator circuits.

If $\begin{pmatrix} C_0 \\ C_1 \\ C_2 \end{pmatrix}$ is the input for each circuit, the outputs given by Pauli-X, Y and Z gates are $\begin{pmatrix} C_2 \\ C_1 \\ C_0 \end{pmatrix}$, $\begin{pmatrix} -\mathrm{i}C_2 \\ C_1 \\ \mathrm{i}C_0 \end{pmatrix}$ and $\begin{pmatrix} C_0 \\ C_1 \\ -C_2 \end{pmatrix}$ respectively.

In each of the following circuits, three channels are used. M is mirror, BS is beam splitter, C_0, C_1 and C_2 are the inputs given in three channels and the outputs are observed at O_1, O_2 and O_3 respectively. The unnecessary changes in phase of light signal due to mirrors, BSs, EDFA, circuit components, etc are ignored here. However, this change in phases can be compensated by using additional EMOs with appropriate applied voltages in every feedback path. EDFAs maintain the intensity of light throughout the channels. The input signal is applied

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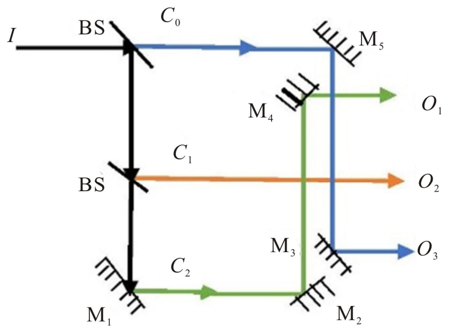
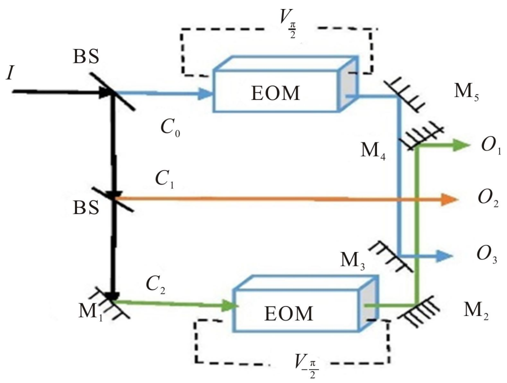
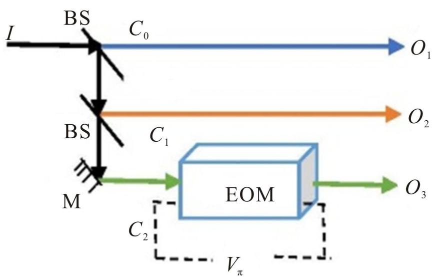
initially and then removed.



(a) Tristate Pauli-X gate



(b) Tristate Pauli-Y gate



(c) Tristate Pauli-Z gate

Fig.1 Circuit diagrams for tristate Pauli-X, Y and Z logic gates

Fig.2 represents the tristate oscillator circuit with tristate Pauli-X gate. The EMO in the feedback path of the middle channel provides a phase shift by π. The outputs at O_1 and O_3 are made continuous by proper feedback arrangements as shown in circuit diagram and the output at O_2 is oscillating its phase between 0 to π with respect to initial input of this channel.

Fig.3 represents the circuit diagram for tristate oscillator with tristate Pauli-Y gate. Here, an EMO is connected at the feedback path from O_3 to C_0 which gives $+\frac{\pi}{2}$ phase lead of feedback signal with respect to initial input at C_0. Another EMO is used in the feedback path from O_1 to C_2 which makes the feedback signal in-phase with initial input at C_2 by providing a phase lead by $\frac{\pi}{2}$. The outputs at O_1 and O_2 are kept constant and continuous and the output at O_3 oscillates its phase between $+\frac{\pi}{2}$ and $-\frac{\pi}{2}$ with respect to initial input C_0.

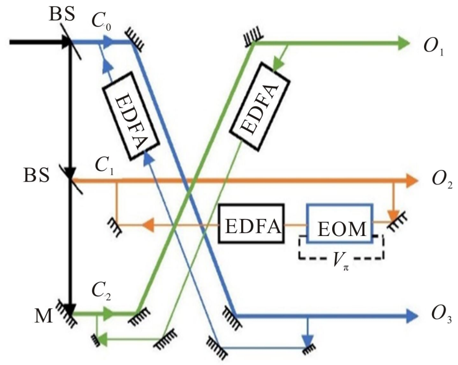


Fig.2 Circuit diagram for tristate oscillator based on tristate Pauli-X gate

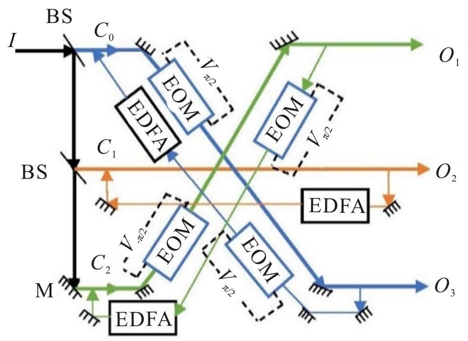


Fig.3 Circuit diagram for tristate oscillator based on tristate Pauli-Y gate

Fig.4 is the circuit diagram for the tristate oscillator with tristate Pauli-Z gate. In this case one EMO is used in the feedback path of lower channel from O_3 to C_2 which gives an additional π phase lead. the outputs at O_1 and O_2 are kept fixed and the phase oscillating output is observed at the channel O_3. In this case, the phase of the light signal is oscillating between π to 2π (or zero) with respect to initial input of this channel.

The operation of tristate quantum oscillator circuit based on tristate Pauli-Z gate is simulated using MATLAB Simulink blocks, which is shown in Fig.5.

In the oscillator circuit, the tristate Pauli-Z gate is operating in addition of feedback signal. The initial input can be chosen randomly. The initial input should be removed after one step of operation. After that the circuit should show the oscillatory operation by using the feedback signals only.

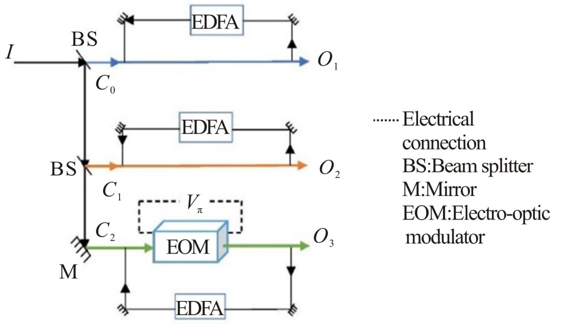
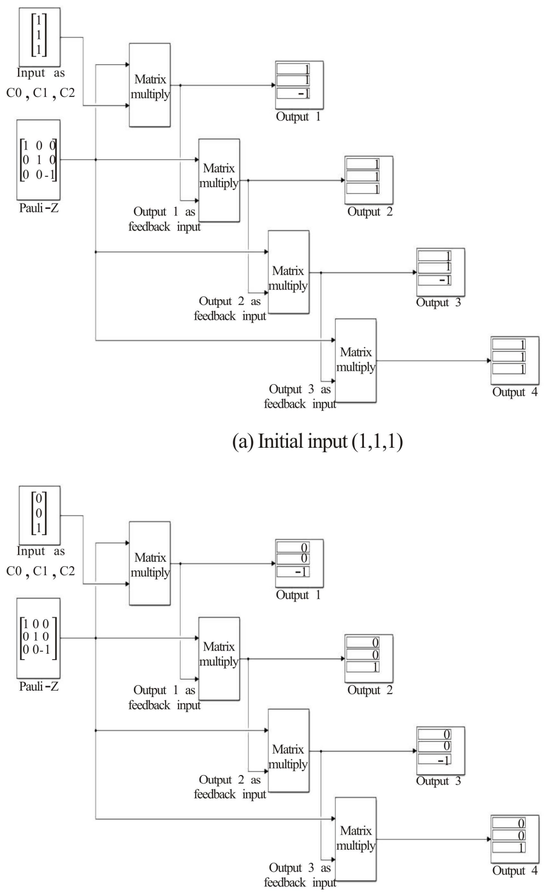


Fig.4 Circuit diagram for tristate oscillator based on tristate Pauli-Z gate

The gate-matrix for tristate Pauli-Z gate is $\begin{bmatrix} 1 & 0 & 0 \\ 0 & 1 & 0 \\ 0 & 0 & -1 \end{bmatrix}$.



(a) Initial input (1,1,1)

(b) Initial input (0,0,1)

Fig.5 Simulation blocks for the operation of tristate quantum oscillator circuit based on tristate Pauli-Z gate

In Fig.5(a), the initial inputs in three channels are chosen as $\begin{pmatrix} 1 \\ 1 \\ 1 \end{pmatrix}$ and the outputs after one step operation are observed as $\begin{pmatrix} 1 \\ 1 \\ -1 \end{pmatrix}$. In the second step, the output of the first step $\begin{pmatrix} 1 \\ 1 \\ -1 \end{pmatrix}$ works as the input signal which comes through the feedback path and gives the output as $\begin{pmatrix} 1 \\ 1 \\ 1 \end{pmatrix}$. This continues until it is stopped. The very initial input is not working anymore after the first step of operation. In whole operation, the output states at upper and middle channels remain constant at 1 and the output states at lower channel is oscillating between −1 to +1, i.e., the phase of the state is oscillating between π and 0 with respect to very initial state 1.

In Fig.5(b), the same operation is shown with an initial state as $\begin{pmatrix} 0 \\ 0 \\ 1 \end{pmatrix}$. In this case, the outputs are observed as $\begin{pmatrix} 0 \\ 0 \\ -1 \end{pmatrix}, \begin{pmatrix} 0 \\ 0 \\ 1 \end{pmatrix}, \begin{pmatrix} 0 \\ 0 \\ -1 \end{pmatrix}$ and so on. This shows that the output states at upper and middle channels are always 0 state and the output states at lower channel is oscillating between −1 and +1 states.

This type of operation is true for all other initial inputs. Thus, the MATLAB simulation of tristate quantum oscillator circuit with tristate Pauli-Z gate verifies its operation which is developed theatrically.

The operation of tristate oscillators based on tristate Pauli-X and Y gates can also be verified in similar way.

In proposed tristate oscillator circuits, the output signal remains fixed at two of the three channels and the output signal at other channel oscillates its phase, keeping other parameters constant. The ranges of oscillating phases are made different for different oscillator circuits. Truth tables and phase outputs for all three tristate oscillator circuits are shown below.

In tristate oscillator with tristate Pauli-X gate, the outputs at the channels O_1 and O_3 are always remain the same and the phase oscillating output is observed only at O_2. The phase of light signal oscillates between 0 and π with respect to initial input C_1 of this channel. The truth table and the oscillating phase output are shown in Tab.1 and Fig.5 respectively.

For tristate Pauli-Y gate-based oscillator, the outputs at the channels O_1 and O_2 are fixed and the phase of the output at O_3 is oscillating from $+\frac{\pi}{2}$ to $-\frac{\pi}{2}$ with respect to initial input C_0 of channel O_1. Tab.2 and Fig.6 give the truth table and the nature of oscillating phase output respectively for the tristate Pauli-Y gate-based oscillator.

Tab.1 Truth table for tristate oscillator circuit based on tristate Pauli-X gate

Remarks	Inputs (including feedback)			Outputs		
	C_0	C_1	C_2	O_1	O_2 (Oscillatory)	O_3
Initial inputs are given to all channels and then inputs are removed.	1	1	1	1	1	1
	1	−1	1	1	−1	1
	1	1	1	1	1	1
	1	−1	1	1	−1	1
Initial input is given to only the channel-2 (C_1) and then the input is removed.	0	1	0	0	1	0
	0	−1	0	0	−1	0
	0	1	0	0	1	0
	0	−1	0	0	−1	0

Tab.2 Truth table for tristate oscillator circuit based on tristate Pauli-Y gate

Remarks	Inputs (including feedback)			Outputs		
	C_0	C_1	C_2	O_1	O_2	O_3 (Oscillatory)
Initial inputs are given to all channels and then inputs are removed.	1	1	1	−i	1	i
	−1	1	1	−i	1	−i
	1	1	1	−i	1	i
	−1	1	1	−i	1	−i
Initial input is given to only the channel-1 (C_0) and then the input is removed.	1	0	0	0	0	i
	−1	0	0	0	0	−i
	1	0	0	0	0	i
	−1	0	0	0	0	−i

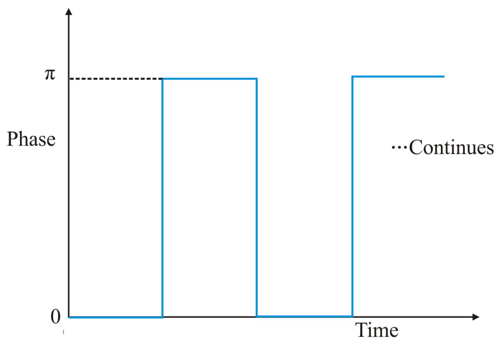


Fig.6 Oscillating phase output for tristate oscillator based on tristate Pauli-X gate

In tristate Pauli-Z gate-based oscillator circuit, the phase oscillating output is observed in channel O_3 while outputs at other two channels remain constant. Truth table of tristate oscillator with tristate Pauli-Z gate is shown in Tab.3. Here, the phase of oscillating output oscillates between π and 2π (or zero) with respect to initial input C_2 at this channel. The corresponding phase output is shown in Fig.7.

Tab.3 Truth table for tristate oscillator based on tristate Pauli-Z gate

Remarks	Inputs (including feedback)			Outputs		
	C_0	C_1	C_2	O_1	O_2	O_3 (Oscillatory)
Initial inputs are given to all channels and then inputs are removed.	1	1	1	1	1	−1
	1	1	−1	1	1	1
	1	1	1	1	1	−1
	1	1	−1	1	1	1
Initial input is given to only the channel-3 (C_2) and then the input is removed.	0	0	1	0	0	−1
	0	0	−1	0	0	1
	0	0	1	0	0	−1
	0	0	−1	0	0	1

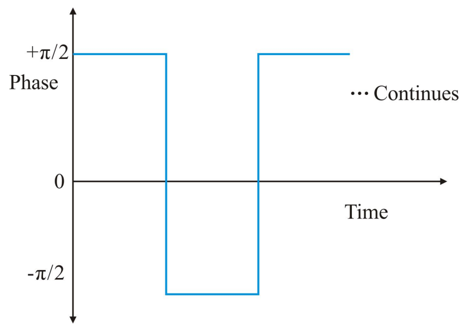


Fig.7 Oscillating phase output for the tristate oscillator based on tristate Pauli-Y gate

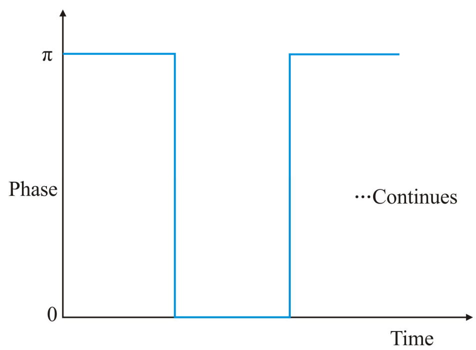


Fig.8 Oscillating phase output for tristate oscillator based on tristate Pauli-Z gate

Here, three different oscillator circuits are developed based on tristate Pauli-X, Y and Z gates respectively. The ranges of oscillating phases are made different in three different circuits to introduce varieties of operations with these circuits. In each circuit, outputs in two of three channels are kept fixed and the phase of the output in other channel is oscillated. The operation of tristate oscillator circuit based on tristate Pauli-Z gate is verified in MATLAB simulation. Other circuits can also be simulated in a similar way. All three channels in oscillator circuits are available to produce oscillating output. One of those three is chosen here to show the oscillation. Again, oscillator circuits can also be designed to get oscillating outputs in multiple channels at the same time. EDFAs are used in the feedback paths to maintain the sufficient intensity of light signal throughout its path of travelling. Additional EOMs can be used in every feedback path to avoid the unnecessary change in phase of light signal during travelling. Designed circuits are all optical ones which ensure high speed of operation.

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Statements and Declarations

The authors declare that there are no conflicts of interest related to this article.

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