Performance analysis of all optical-based quantum internet circuits

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Abstract
A Quantum dot implanted within a double-sided optical microcavity is considered and investigated as a critical component for all optical-based quantum internets. Due to the duality as the photonic quantum transistor and gate, the QD cavity system represents a sturdy base for the future photonic quantum network. With the help of the analytical investigation and review presented in this paper, a quantum dot cavity unit can be developed for implementing deterministic quantum gates and transistors. The maximum fidelity observed for quantum diode, router, and storage is 95.24, 62.06, and 90.42% without considering a noisy environment, respectively, and 62.12, 60.36, and 43.66% under a noisy environment, respectively. Fidelity is also calculated with varying coupling conditions (strong and weak coupling), and optimized cavity parameters are calculated.

Keywords Quantum computing · Linear optics · Microcavity · Spin · Photonic qubit · Quantum dot (QD)

1 Introduction
Quantum machines have an implausible computational perspective that can address many practical applications such as integer factorization, quantum cryptography, modeling of complex quantum structure, quantum teleportation, and database search (Grover’s algorithm) [1]. The Quantum gate is the fundamental element for quantum computers. Single Qubit unitary gates combined with CNOT gate is the universal set of quantum algorithm realization [2].

Photons are advanced to other Qubit options (atoms, electrons, etc.), as they offer enormous benefits (decoherence and fastest speed). Well-developed optical components are on hand for processing photonic data. Photonic devices are compatible with well-developed semiconductor technologies [3]. In the literature, it has been discussed that single Qubit unitary operations can be implemented efficient way using linear optical elements. In 1998 Cerf et al. demonstrated the design of a CNOT gate using optical components such as phase shifters and beam splitters. In 2001 Grover’s algorithm was implemented using this scheme. A downside of this technique is the exponential increase of the photonic components with the size of the system [4]. The main difficulty in designing a multi-Qubit quantum circuit is the non-interacting nature of photons.

Earlier it was believed that without using nonlinearities, it was not possible to design two Qubit quantum circuits. However, the Kerr-based two Qubit quantum circuits are unfeasible in a single-photon state. In literature, many approaches (2001 Knill et al., 2002 Scott Glancy et al.) for photon interaction have been introduced, but these are non-deterministic approaches. Knill et al. designed a CZ gate using this scheme with a 0.25 success probability [5].

In 2009 Hu et al. proposed a spin-dependent beam splitter using a QD cavity arrangement. The photon interaction problem had been addressed in a deterministic way which was the main challenge for a two-photon quantum gate design. It opens the door to deterministic photonic quantum circuit design employing linear optical elements [6]. 2009 onwards QD cavity system has been investigated for multi-Qubit photonic quantum gate implementation. Cristian Bonato et al. [7] proposed a QD cavity model for providing an interface between photon and the spin of excess electron of QD inside the microcavity under weak coupling conditions.

In 2013 Hong-Fu Wang et al. [8] proposed a circuit for the teleportation of a controlled-NOT gate (spin Qubit based) using a QD cavity unit. In 2013 Hong-Fu Wang et al. demonstrated a photonic CNOT gate using a QD cavity unit. This was the critical research for fully photonics-based quantum
data processing systems [8]. In 2013 Wei et al. investigated the prospect of realizing scalable photonic quantum computing using a QD cavity unit. In 2013 Wei et al. [9] presented a model to realize a QD cavity unit. In 2013 Hong-Fu Wang et al. [10] proposed a scheme for teleportation of CNOT gate using QD cavity unit. In 2014 Wei et al. [11] demonstrated universal quantum gates based on spin Qubits using QD cavity units. Hu et al. [12] presented the quantum gate functionality using a QD cavity. Jino Heo et al. [13] proposed a scheme based on a QD cavity unit for simultaneously transferring and teleporting an unknown state (electron spin) between two users. This scheme is teleporting spin qubits by taking the help of photonic qubits.

Amor Gueddana et al. [14] proposed a QD cavity unit-based model to realize a photonic CNOT gate using quantum cloner. For this scheme, electron spin measurements and ancillary Qubits are not required. This is not a heralded scheme, so practically, fidelity will increase. Min-Sung Kang et al. [15] proposed a deterministic Fredkin gate using a QD cavity unit, which can perform a controlled swap operation between three Qubits. The performance of the designed gate was calculated under noisy conditions and concluded that the designed gate can be implemented experimentally with high efficiency.

For implementing quantum internet, universal quantum gates, memory, and quantum switching (control the flow of data) are vital components. Universal quantum gates have been explored by researchers with high fidelity and efficiency, but still, quantum switching elements were not investigated. Hu [16] explained that an efficient photonic transistor can be designed using a spin cavity unit. It was a milestone in the roadmap of integrated photonic quantum internet. A quantum dot cavity unit has been demonstrated for the physical realization of these quantum components with high feasibility and efficiency. It needs more research to develop a QD cavity unit-based large-scale integrated photonic quantum network.

The work reported in this paper will help researchers to explore the field of all optical-based quantum communication and computing. The article is organized as follows. In Sect. 2 Quantum dot cavity system and interaction mechanism between photon and quantum dot spin are discussed. In Sect. 3 QD cavity unit is demonstrated as a photonic quantum switching component (diode and router) and quantum memory. The performance of quantum circuits is analytically investigated, and optimized cavity parameters are calculated. Finally, the paper is concluded.

Fig. 1 QD within the double-sided cavity

Fig. 2 QD dipole optical transition energy level diagram (Here up (\(|\uparrow\rangle\)) and down (\(|\downarrow\rangle\)) represents the spin state of an excess electron, R and L are right and left circularly polarized photon. Superscript is for the upward and downward propagation direction of a photon inside the cavity) [8]

2 QD cavity systems

In the process of gate functioning cavity works as cold and hot depending on control and target photonic Qubits. Left circularly polarized (LCP) and right circularly polarized (RCP) are used to define input photon as Qubit. The hot or cold cavity depends on the polarization of the input photon, the propagation direction of a photon inside the QD cavity unit, and the spin of the QD electron. The hot cavity or cold cavity is part of the process of designing a quantum gate using a QD cavity unit. It’s not possible to design a quantum gate using only one cavity case (hot or cold cavity). For designing a quantum gate, the QD cavity should work in both hot and cold cavity mode depending on the input photonic Qubits. The quantum dot cavity unit is depicted in Fig. 1 [8].

The optical dipole transition (Energy level diagram) of a QD spin and photon interaction is depicted in Fig. 2 (Wang et al. 2013).

When \(s_z = +1(R^\dagger \text{ and } L^\dagger)\) photon interacts with QD which is in up spin state (\(|\uparrow\rangle\)), the cavity works as a hot cavity. In hot cavity condition, Qubit couples with cavity and both direction of propagation and polarization of photon change. When \(s_z = -1(R^\dagger \text{ and } L^\dagger)\) photon, interact with QD which is in the down spin state (\(|\downarrow\rangle\)), the cavity works as the cold cavity. In the cold cavity condition, Qubit does not couple with cavity and only 180° phasesshift is added to Qubit. For hot cavity regime (\(g \neq 0\)), interaction between the QD spin and photon within a practical cavity arrangement can be articulated as Eqs. (1–4) [8]:

\[
|R^\dagger, \uparrow\rangle = R(\omega)|L^\dagger, \uparrow\rangle + T(\omega)|R^\dagger, \uparrow\rangle
\] (1)
\[
\begin{align*}
|R^1, \downarrow\rangle &= R(\omega)|L^1, \uparrow\rangle + T(\omega)|R^1, \downarrow\rangle \\
|L^1, \downarrow\rangle &= R(\omega)|R^1, \downarrow\rangle + T(\omega)|L^1, \downarrow\rangle \\
|L^1, \uparrow\rangle &= R(\omega)|R^1, \uparrow\rangle + T(\omega)|L^1, \uparrow\rangle \\
|R^1, \downarrow\rangle &= -R(\omega)|R^1, \downarrow\rangle - T(\omega)|L^1, \downarrow\rangle \\
|L^1, \uparrow\rangle &= -R(\omega)|R^1, \uparrow\rangle - T(\omega)|L^1, \uparrow\rangle \\
|R^1, \uparrow\rangle &= -R(\omega)|L^1, \uparrow\rangle - T(\omega)|R^1, \uparrow\rangle \\
|L^1, \downarrow\rangle &= -R(\omega)|L^1, \downarrow\rangle - T(\omega)|R^1, \downarrow\rangle
\end{align*}
\]

Sideband leakage (\(S(\omega)\)), Transmittance (\(T(\omega)\)), noise (\(N(\omega)\)) and reflectance (\(R(\omega)\)) factors for hot cavity (\(g \neq 0\)) condition are expressed by Eqs. (9–12) [8]. Hot cavity case can be understood from Eq. (1) when R photon propagating in up direction inside QD cavity (\(R^1\)) interacts with QD excess electron spin in upstate (\(\uparrow\)). Ideally in hot cavity case \(R(\omega) = 1\) and \(T(\omega) = 0\). After interaction under ideal condition R photon will become L photon and propagation direction will be downwards inside QD cavity. But in practical condition \(R(\omega) \neq 1\) and \(T(\omega) \neq 0\). So some portion of photon will transmit through cavity without interaction (\(|R^1, \uparrow\rangle\)) and some portion will reflect with change in polarisation and direction of propagation (\(|L^1, \uparrow\rangle\)). Similarly, interaction dynamics for the cold cavity regime (\(g = 0\)) are described by Eqs. (5–8) [8]:

\[
\begin{align*}
|L^1, \downarrow\rangle &= -R_0(\omega)|R^1, \downarrow\rangle - T_0(\omega)|L^1, \downarrow\rangle \\
|L^1, \uparrow\rangle &= -R_0(\omega)|R^1, \uparrow\rangle - T_0(\omega)|L^1, \uparrow\rangle \\
|R^1, \uparrow\rangle &= -R_0(\omega)|L^1, \uparrow\rangle - T_0(\omega)|R^1, \uparrow\rangle \\
|R^1, \downarrow\rangle &= -R_0(\omega)|L^1, \downarrow\rangle - T_0(\omega)|R^1, \downarrow\rangle
\end{align*}
\]

Cold cavity case can be understood from Eq. (5), when L photon propagating downside in QD cavity (\(L^1\)) interacts with QD excess electron spin in down state (\(\downarrow\)). Ideally \(T_0(\omega) = 1\) and \(R_0(\omega) = 0\). Under ideal condition L photon will transmit through cavity without change in polarization and direction of propagation. But in practical condition \(T_0(\omega) \neq 1\) and \(R_0(\omega) \neq 0\), so some portion of input photon will reflect (\(|R^1, \downarrow\rangle\)) and some portion will transmit through cavity (\(|L^1, \down\rangle\)).

\[
R(\omega) = \frac{i(\omega_c - \omega)}{(\omega_c - \omega) + \frac{k^2}{2} + \frac{\hbar^2}{\omega_c - \omega + \gamma}}
\]

\[
T(\omega) = \frac{-k}{i(\omega_c - \omega) + \frac{k^2}{2} + \frac{\hbar^2}{\omega_c - \omega + \gamma}}
\]

\[
S(\omega) = \frac{\sqrt{k\hbar}}{i(\omega_c - \omega) + \frac{k^2}{2} + \frac{\hbar^2}{\omega_c - \omega + \gamma}}
\]

Where \(\omega_c\), \(\omega_X\), and \(\omega\) are the frequencies of cavity, transition and the incoming photon respectively. \(k\), \(k\) and \(g\) are the side leakage rate of the cavity, field decay rate and the coupling strength respectively. \(\gamma/2\) is QD dipole decay rate. Similarly, sideband leakage (\(S_0(\omega)\)), transmittance (\(T_0(\omega)\)), noise (\(N_0(\omega)\)) and reflectance (\(R_0(\omega)\)) factors for cold cavity (\(g = 0\)) conditions can be expressed [8]. If we consider a noisy environment, then transmission and reflection factors \(r_0, r_0, r_0, r_0, r_0\) and \(t\) are given by Eqs. (13–16)

\[
r_0 = S_0(\omega) + R_0(\omega)
\]

\[
r = S(\omega) + R(\omega) + N(\omega)
\]

\[
t_0 = S_0(\omega) + T_0(\omega)
\]

\[
t = N(\omega) + T(\omega) + S(\omega)
\]

Without noisy environment reflection and transmission factors, \(r_0, r_0, r_0, r_0, r_0\), and \(t\) are the same as \(R_0(\omega), T_0(\omega), R(\omega), T(\omega)\). Quantum dot cavity arrangement can be explored to implement photonic quantum switches, routers, and DRAM.

### 3 Result and discussion

Ideally, under cold cavity condition, \(R(\omega) = 0\), and \(T(\omega) = 1\), and under hot cavity condition, \(R(\omega) = 1\) and \(T(\omega) = 0\). In practical cases, quantum dot cavity response depends on cavity factors and input photons. Amplitude and phase of cavity factors are plotted with detuning \((\omega - \omega_c)/k\) using Eqs. (9–12). We have considered that \(\omega_c = \omega_X\) and \(\gamma/2 = 0.1\).

Transmission and reflection coefficient are plotted with detuning and different coupling conditions as shown in Figs. 3 and 4. Dotted and solid lines are corresponding to cold and hot cavity conditions and colors (red, blue and black) are for different coupling conditions. The amplitude and phase of transmission and reflection coefficient are depending on frequency of input photonic Qubit. At \((\omega - \omega_c) = 0\), it can be observed that for hot cavity, reflection coefficient is maximum and for cold cavity, reflection coefficient is minimum. The requirement for hot cavity conditions is that the photon should interact with QD excess electron and reflect. Similarly at zero detuning, transmission coefficient for cold cavity is maximum and for hot cavity transmission coefficient is minimum. The requirement of cold cavity is that the photon should pass through QD cavity.
Fig. 3 Reflection $R(\omega)$ v/s detuning $(\omega - \omega_c)/k$

![Graph showing reflection](image)

Fig. 4 Transmission $T(\omega)$ v/s detuning $(\omega - \omega_c)/k$

![Graph showing transmission](image)
without any interaction. Transmission and reflection coefficients are also depending on coupling strength (black, blue and red lines are corresponding to different coupling conditions). So for correct functioning of QD cavity unit-based quantum circuits, coupling strength and detuning should be chosen in such a way that under cold cavity transmission coefficient should be maximum and under hot cavity condition, reflection coefficient should be maximum.

Similarly, noise and sideband leakage factors are plotted in Figs. 5 and 6 with detuning and different coupling conditions. Noise is zero under cold cavity condition, so noise factor plots are only for hot cavity condition. At zero detuning sideband leakage is minimum for hot cavity and maximum for cold cavity conditions. Noise and sideband leakage should be as less as possible for better functioning of quantum circuit. So detuning and coupling should be chosen in such a way that for both under hot and cold cavity cases these factors (noise and sideband leakage) should be minimum. It is noted from Figs. 3, 4, 5 and 6 that these coefficients are strongly interrelated with coupling and detuning. Thus the performance of the QD cavity-based quantum circuits depends on cavity parameters (noise, coupling strength, sideband leakage rate, and cavity mode decay rate) and input Qubits. To measure the performance of the quantum circuit, the average of fidelity (AOF) can be expressed as Eq. (17) [18]. The average of fidelity is a parameter that defines the closeness of two quantum states. The fidelity is used to decide how noisy a quantum circuit is.

$$AOF = \frac{1}{2\pi} \int_{0}^{2\pi} d\theta |<\psi_{s}|\psi_{t}>|^2$$  \hspace{1cm} (17)

The output of the ideal quantum circuit is |ψs>, and |ψt> is the final state of the quantum circuit under practical conditions. The final state |ψt> is found analytically using the interaction mechanism of a photon and a quantum dot inside a double-sided optical cavity.

### 3.1 QD cavity systems as quantum Diode

The diode is the basic component for quantum switching. According to Pauli’s exclusion principle (spin selection rule), the transmission or reflection of a photon depends on the spin of QD excess electron in the quantum dot cavity unit. A photonic diode can be implemented by using a QD cavity unit, as shown in Fig. 7. According to the spin selection rule of a QD cavity unit, the right circularly photon will transmit through the cavity if QD spin is up and reflect from the cavity if QD spin is down. Similarly, it can be understood for the left circularly polarized photon. Figure 7 is the case when the diode is on (the device will pass photon. So by controlling the spin of QD excess electron, the diode can be set ON or OFF for incoming photons [17].
If \((\cos \theta_1 |R > + \sin \theta_1 |L >)\) is applied to the quantum diode circuit as shown in Fig. 7. The final output state is found using Eqs. (5–8) and expressed as

\[
|\psi_t \rangle = t_0 \cos \theta_1 |R > + t_0 \sin \theta_1 |L >
\]  

(18)

The Fidelity of the quantum diode has been calculated using Eqs. (17 and 18) and plotted with varying cavity (strong and weak coupling regime; instead, it depends on sideband leakage.

3.2 QD cavity systems as a quantum router

Quantum routers control the flow of information (photonic Qubits) on a quantum network. Quantum routers can be implemented using the QD cavity unit, as shown in Fig. 9a. When \(|\psi > = \delta |R > + \gamma |L >\) signal is applied at the input port of the QD cavity unit, the R photon will transmit through the cavity, and the L photon will reflect from the cavity. L photon is passed through switches and applied to c-PBS (circularly polarizing beam splitter), and for synchronizing, L photon first passes through a delay line (D) and then applied to c-PBS. C-PBS is designed in such a way that it passes the L photon and reflects the R photon. So the output of the system is provided at port J. Similarly system designed in Fig. 9b can be explained, and the output is provided at port K. So, the input signal can be routed at port J or port K by controlling the spin of the quantum dot.

If \((\cos \theta_1 |R > + \sin \theta_1 |L >)\) is applied to the quantum router circuit as shown in Fig. 9a. The final output state is found at port J using Eq. (5–8) and expressed as

\[
|\psi_t \rangle = t_0 \cos \theta_1 |R > + t_0 \sin \theta_1 |L >
\]  

(19)

The Fidelity of the quantum router has been calculated using Eqs. (17 and 19) and plotted with varying cavity...
parameters, as shown in Fig. 10, with and without considering noisy conditions. It is observed from Fig. 10 that fidelity is strongly correlated with coupling and leakage rates. The computed maximum fidelity of the photonic quantum router is 60.36 at $g/k = 0.3$ and $k_s/k = 0.1$ without noisy conditions and 62.06 at $g/k = 4$ and $k_s/k = 0.1$ without noisy conditions, respectively. Maximum fidelity is achieved in strong coupling regime without noisy conditions and in a weak coupling condition under noisy environment.

### 3.3 QD cavity systems as quantum memory

Quantum memories are used to store quantum information (photonic Qubit). Quantum memories can be realized using a QD cavity unit, as shown in Fig. 11. Initially, if the L photon is applied to the QD cavity unit, and the spin of the QD excess electron is set to down ($\downarrow$) spin. So, according to Pauli’s exclusion, the photon doesn’t couple with the cavity (cold cavity), and it is transmitted in the second cavity (downside mirror of the second cavity is fully reflective). Then spin of QD excess electron is changed to up ($\uparrow$) spin. Now cavity acts as a hot cavity and reflects the photon. Photon resonates and stored in the second cavity until QD electron spin is changed. If QD spin is changed to upstate QD cavity unit acts as cold and transmits the photon, which can be read. Similarly, it can be explained for R photon also.

If $(\cos \theta_1 |R\rangle + \sin \theta_1 |L\rangle)$ is applied to the quantum memory circuit, as shown in Fig. 11. R photon is reflected and L photon is transmitted from c-PBS. R photon will interact with first QD cavity unit and L photon interacts with second QD cavity unit. To achieve the storage process, quantum dot spin is changed so the cavity will act as a hot cavity, and photons will be reflected back in the lower cavity. If we consider one-time reflection or hot cavity condition. So if storage time increases, more reflection coefficients occur in
the final state. Now for the read operation again, quantum dot spin is changed, so the quantum dot cavity unit acts as a cold cavity, and the photon is available for reading. The final output state is found using Eq. (5–8) and expressed as

$$|\psi_t> = t_0 t_0^* R \cos \theta |R> + t_3 t_0^* L \sin \theta |L>$$ (20)

It is noted from Fig. 12 that the maximum fidelity achieved for the memory is 90.42 at $g/k = 4$ and $k_s/k = 0.1$ and 43.66 at $g/k = 0.5$ and $k_s/k = 0.1$ with and without noisy conditions, respectively. Maximum fidelity is achieved in a strong coupling regime in both cases. Maximum fidelity is greatly affected by sideband leakage and noise. Read process fidelity is also depending on storage time. If information is read after significant time, fidelity of the reading process will decrease.

4 Conclusion

This paper analytically investigates the photonic quantum diode, router, and memory designed using QD cavity system and linear optics. The performance parameter (fidelity) is analytically calculated. It has been noted that fidelity strongly depends on the coupling regime (strong and
weak). The performance of quantum switching circuits is greatly affected by quantum noise and sideband leakage. The optimum performance parameter of QD cavity-based photonic quantum circuits can be found using the analytical investigation presented in this paper. The Quantum cloner model can be used to further improve the performance of quantum circuits. Physically scalable multi-Qubit quantum circuit design, Quantum Simulators, quantum algorithms to advance state-of-the-art quantum computers, and quantum error correction codes are some areas that can be explored to implement quantum internet.

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Data availability Enquiries about data availability should be directed to the authors.

Declarations

Conflict of interest There is no conflict of interest.

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