Optical Bistability and Absorption characteristic of an Optomechanical system embedded with double quantum dot and nonlinear medium.

Surabhi Yadav (surabhiyadav52@gmail.com)
Birla Institute of Technology & Science Pilani - Hyderabad Campus https://orcid.org/0000-0002-5128-9401

Vijay Bhatt
: University of Delhi Department of Physics and Astrophysics

Aranya B Bhattacherjee
Birla Institute of Technology & Science Pilani - Hyderabad Campus

Pradip K. Jha
DDU College: Deen Dayal Upadhyaya College

Sanchita Roy
University of science and Technology Meghalaya

Research Article

Keywords:

Posted Date: July 5th, 2022

DOI: https://doi.org/10.21203/rs.3.rs-1644640/v1

Optical Bistability and Absorption characteristic of an Optomechanical system embedded with double quantum dot and nonlinear medium

Surabhi Yadav[1], Vijay Bhatt[2], Aranya B Bhattacherjee*[1,3], Pradip K. Jha[4] and Sanchita Roy[3]

[1]*Department of Physics, Birla Institute of Technology and Science, Pilani, Hyderabad Campus, Telangana 500078, India*

[2] *Department of Physics and Astrophysics, University of Delhi, New Delhi 110009, India*

[3]*Department of Physics, School of Applied Sciences, University of Science and Technology, Ri-Bhoi, Meghalaya-793101, India*

[4] *Department of Physics, DDU College, University of Delhi, New Delhi 110078, India**

Objective: This paper theoretically studies a hybrid optomechanical system embedded with two coupled quantum dots (CQDs) and a third-order Kerr nonlinear medium inside the cavity. The optical bistability and absorption spectrum are analyzed for the proposed system.

Methods: From the Hamiltonian which describes the proposed system, a set of quantum Langevin equations are derived. Using these equations of motion, the steady-state mean field analysis is done which gives the phenomena of optical bistability. The performance of the optical switch is also analyzed in terms of gain and switching ratio. Further, the absorption spectrum of the system is derived and analyzed from the fluctuation dynamics.

Results: The optical bistability has the potential to design tunable all-optical switches. The absorption spectra display peculiar characteristics of negative absorption (transparency dip). The transparency dips are found to be strongly dependent on the frequency of the mechanical resonator. The results of our investigation reveal that the proposed system can be used as an optical switch and has numerous other applications in quantum communication systems.

I. INTRODUCTION

With recent theoretical studies and tremendous technological developments, quantum optomechanics has emerged as a well-developed and effective tool for many quantum manipulation. In an optomechanical system, an optical field coupled to the mechanical oscillator via radiation pressure has emerged as a rapidly developing field of research [1, 2]. This optomechanical interaction has led to various applications such as atomic force microscopes [3], quantum entanglement [4, 5], gravitational wave interferometers [6], quantum information processing [7], optomechanically induced transparency [8, 9], and ultra-high precision measurement [10]. In addition placing a $\chi^{(3)}$ medium inside a cavity produces massive optical Kerr nonlinearities [34]. There is a strong nonlinear interaction between photons as a result of the $\chi^{(3)}$ medium. The Kerr medium is found to be a new handle to efficiently control the micro-mirror dynamics and this suggests a possibilities of designing a new quantum device.

The Quantum dots are optically active semiconductor nanocrystals that constrain the movement of both holes and electrons in regions of space comparable to or smaller than the exciton Bohr radius. They are also called "artificial atoms" because of the confinement of charge carriers in three-dimension. Semiconductor quantum dots (QDs) are promising candidates for developing hybrid quantum devices due to their large density of states, narrow line-widths, and capability to implement optoelectronic devices with optical tunability [11–13]. Quantum dots confined in micro-cavities provides an ideal system to study cavity quantum electrodynamics which is the most straightforward way of obtaining single-photon nonlinear behavior. Quantum dot molecules (QDMs) are systems formed by two or more closely packed and interacting QDs. Quantum dot molecules are experimentally fabricated using either epitaxial growth or chemical synthesis by self-assembly technique [14]. Compared to a single QD, the states in a double QD are significantly changed, leading to applications such as conditional quantum control [15], entangled photon source [16], and spin flip-flop [17], providing a new way to implement a two-qubit quantum gate. Various theoretical methods have studied coupled double quantum dots (CDQDs). Edgar A et al. [18] studied a dissipative quantum dot microcavity system interacting with a nonlinear optical interaction. Dipole-dipole interaction in which one QD absorbs a photon released by the

*Electronic address: aranyabhuti@hyderabad.bits-pilani.ac.in

other excited QD is also studied to characterize CDQDs. This interaction has been used to study remote entanglement states [19]. Quantum interference and coherence can be induced by the tunneling of electrons between the dots, controlled by an external electric field [20, 21]. As a result, fundamental double quantum dot studies such as optical bistability [22], entanglement [23], enhanced Kerr nonlinearity [24], fluorescence spectrum narrowing [25], EIT and slow light [26], coherent population transfer [27] are being investigated.

Optical bistability (OB) is an interesting nonlinear quantum optical phenomenon that has attracted a great deal of attention because of its potential in wide applications such as in optical memory, logic circuits, all-optical switches which are critical in telecommunication applications [28]. Over the past few years, studies have shown various ways [22] to control OB, such as electromagnetically induced transparency (EIT), spontaneously generated coherence, and phase fluctuation. Optical switching (OS) in the semiconductor QDs and quantum wells (QWs) have been followed with a great deal of interest for many properties such as strong optical nonlinearity and excellent flexibility in devices [29]. In recent years, there has been much interest in exploring OB in nonlinear nanophotonic systems [30]. Optical bistability has been investigated experimentally and theoretically predicted to exist in photonic crystal cavities [31], metal gap waveguide nanocavities [32], and waveguide-ring resonators [33]. The loss of power at frequencies in metal interconnects is one of the most significant problems associated with high-speed electronic devices. All-optical switches with low laser power consumption are new for developing novel quantum technologies.

Electromagnetically induced transparency (EIT) has played a crucial role in many subfields of quantum optics. EIT is a quantum interference effect caused by different optical field transition pathways [35]. Both absorption and dispersion properties change dramatically within the transparency window, leading to many applications, including slow light and optical storage [36].

This paper investigates the OB and absorption characteristics of a double quantum dot molecule embedded in an optomechanical cavity interacting with a Kerr nonlinear medium.

II. THEORETICAL MODEL

In our proposal, we consider a hybrid optomechanical system comprising of two coupled quantum dots embedded in a $\chi^{(3)}$ nonlinear photonic crystal optomechanical cavity. InAs

QDs and GaAs photonic crystal cavity have been easily integrated using well-known techniques [37, 38]. The photonic crystal cavity mode can interact with either one or two nearby QDs located precisely at the cavity electric field maximum [37]. The density of the embedded QDs can range between zero to 3 per μm^2 [39–41]. Numerous experimental techniques are available to fabricate a photonic crystal cavity integrated optomechanical system [42, 43]. In addition, a $\chi^{(3)}$ nonlinear 2D layered medium is grown in the photonic crystal cavity using known techniques [44–46].

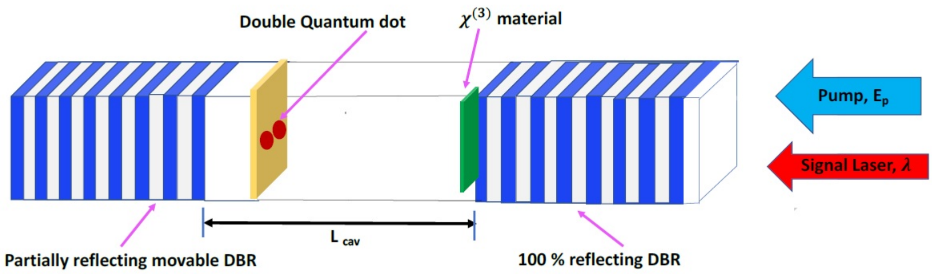

Figure 1: Schematic diagram of an optomechanical system comprising two CDQDs embedded in a photonic crystal cavity. DBR mirrors form the cavity mode. The blue stripe is the AlGaAs layer, whereas the GaAs layer is the white strip. A Kerr nonlinear medium is attached to the cavity, and the resulting photons from the nonlinear process are directly injected into the cavity. The cavity is driven by the strong pump field and weak probe field.

The proposed model in the rotating wave (frame rotating at the pump frequency ω_p) and dipole approximation can be described by the following optomechanical Hamiltonian, taking $\hbar = 1$ as,

$$H = \Delta_a a^\dagger a + \Delta_{d1}\sigma_z^{(1)} + \Delta_{d2}\sigma_z^{(2)} + \frac{\omega_m}{2}(p^2+q^2) + \beta a^\dagger a^\dagger aa + \Omega_1(a^\dagger\sigma_-^{(1)} + a\sigma_+^{(1)}) + \Omega_2(a^\dagger\sigma_-^{(2)} + a\sigma_+^{(2)}) + 2M_z\sigma_z^{(1)}\sigma_z^{(2)} + \omega_D\sigma_+^{(1)}\sigma_-^{(2)} + \omega_D\sigma_-^{(1)}\sigma_+^{(2)} - Ga^\dagger aq + E_p(a+a^\dagger) + E_s(ae^{\iota\delta t} + a^\dagger e^{-\iota\delta t}), \quad (1)$$

where $\Delta_a = \omega_a$ - ω_p, $\Delta_{d1} = \frac{\omega_{d1}}{2}$ - ω_p, $\Delta_{d2} = \frac{\omega_{d2}}{2}$ - ω_p.

Here, a ($a^\dagger$) are the annihilation (creation) operators of the photonic crystal cavity mode. The first four terms are the free energies of the cavity mode, the two quantum dots and the mechanical mode respectively. The cavity frequency is ω_a, the QD frequencies are ω_{d1} and ω_{d2} while ω_m is the natural frequency of the mechanical oscillator. Here $\sigma_\pm^{(1)}$ and $\sigma_\pm^{(2)}$ are the electronic transition operators of the two levels in first and second QD respectively. Further $\sigma_z^{(1)}$ and $\sigma_z^{(2)}$ denotes the population difference between the two energy levels of the first and second QD respectively. Here p and q are the normalized momentum and the position operators of the oscillator respectively. The fifth term is the Kerr nonlinearity with β as the nonlinear strength of the nonlinearity. β depends on the nonlinear susceptibility $\chi^{(3)}$ and the cavity mode volume as $\beta = 3\omega_a^2\ \mathrm{Re}[\ \frac{\chi^{(3)}}{2\epsilon_0 V_c}]$ with V_c as the cavity volume [47–49]. The sixth and seventh terms represent the QD-optical cavity mode coupling with interaction strengths Ω_1 and Ω_2 for the first and second QD respectively. The eighth term corresponds to the dipole-dipole interaction between the two QDs with strength M_z. The ninth and tenth terms refer to the Forster interaction between the two QDs with ω_D as the rate at which energy is transferred between the QDs. The eleventh term is the typical nonlinear optomechanical interaction term with G as the single photon optomechanical strength. The optomechanical strength $G = \frac{\omega_a}{L_{cav}}\sqrt{\frac{\hbar}{m\omega_m}}$ with L_{cav} as the length of cavity. The twelfth term is the strong optical pump with E_p as the rate at which energy is pumped into the cavity and ω_p as the pump frequency. Finally the thirteenth term is the weak probe/signal with strength as E_s and $\delta = \omega_s$ - ω_p, where ω_s is the signal frequency. It is important to note that the nonlinear $\chi^{(3)}$ material is not directly pumped. Using the Hamlitonian of equation (1), the dynamics of the proposed system can be described by the quantum Langevin equations which are derived as,

$$\dot{a} = -\iota\Delta_a a - \kappa_a a - \iota\Omega_1\sigma_-^{(1)} - \iota\Omega_2\sigma_-^{(2)} - 2\iota\beta|a|^2 a + \iota G a q - \iota E_p - \iota E_s e^{-\iota\delta t}, \tag{2}$$

$$\dot{\sigma}_-^{(1)} = -\iota\Delta_{d1}\sigma_-^{(1)} - \kappa_{d1}\sigma_-^{(1)} + 2\iota\Omega_1 a\sigma_z^{(1)} - 2\iota M_z\sigma_-^{(1)}\sigma_z^{(2)} + 2\iota\omega_D\sigma_z^{(1)}\sigma_-^{(2)}, \tag{3}$$

$$\dot{\sigma}_-^{(2)} = -\iota\Delta_{d2}\sigma_-^{(2)} - \kappa_{d2}\sigma_-^{(2)} + 2\iota\Omega_2 a\sigma_z^{(2)} - 2\iota M_z\sigma_-^{(2)}\sigma_z^{(1)} + 2\iota\omega_D\sigma_z^{(2)}\sigma_-^{(1)}, \tag{4}$$

$$\dot{\sigma}_z^{1} = -\Gamma_1(\sigma_z^{(1)} + 1) + \iota\Omega_1(a^\dagger\sigma_-^{(1)} - \sigma_+^{(1)}a) - \iota\omega_D\sigma_+^{(1)}\sigma_-^{(2)} + \iota\omega_D\sigma_-^{(1)}\sigma_+^{(2)}, \tag{5}$$

$$\dot{\sigma}_z^{2} = -\Gamma_2(\sigma_z^{(2)} + 1) + \iota\Omega_2(a^\dagger\sigma_-^{(2)} - \sigma_+^{(2)}a) - \iota\omega_D\sigma_+^{(2)}\sigma_-^{(1)} + \iota\omega_D\sigma_-^{(2)}\sigma_+^{(1)}, \tag{6}$$

$$\dot{q} = \omega_m p, \tag{7}$$

$$\dot{p} = -\omega_m q + G a^\dagger a - \gamma_m p. \tag{8}$$

Here κ_a is the decay rate of the cavity mode. The dephasing rate of the first and second QD is κ_{d1} and κ_{d2} respectively. The decay rate of the mechanical mode is γ_m and Γ_1 and Γ_2

are the relaxation rate of the first and second QD respectively. In order to solve equations (2)-(8), we make the following ansatz [50, 51],

$$\begin{aligned}
a(t) &= a_0 + a_{(+)}e^{-\iota\delta t} + a_{(-)}e^{\iota\delta t},\\
\sigma_-^{(1)}(t) &= \sigma_0^{(1)} + \sigma_{(+)}^{(1)}e^{-\iota\delta t} + \sigma_{(-)}^{(1)}e^{\iota\delta t},\\
\sigma_-^{(2)}(t) &= \sigma_0^{(2)} + \sigma_{(+)}^{(2)}e^{-\iota\delta t} + \sigma_{(-)}^{(2)}e^{\iota\delta t},\\
\sigma_z^{(1)}(t) &= \sigma_{0z}^{(1)} + \sigma_{(+)z}^{(1)}e^{-\iota\delta t} + \sigma_{(-)z}^{(1)}e^{\iota\delta t},\\
\sigma_z^{(+)}(t) &= \sigma_{0z}^{(2)} + \sigma_{(+)z}^{(2)}e^{-\iota\delta t} + \sigma_{(-)z}^{(2)}e^{\iota\delta t},\\
q(t) &= q_0 + q_{(+)}e^{-\iota\delta t} + q_{(-)}e^{\iota\delta t},\\
p(t) &= p_0 + p_{(+)}e^{-\iota\delta t} + p_{(-)}e^{\iota\delta t}.
\end{aligned} \tag{9}$$

We will be working to the lowest order in E_s, but to all orders in E_p. The linear susceptibility for first exciton is given as,

$$\chi_{eff}^{(1)} = \frac{\sigma_+^{(1)}}{E_s} \tag{10}$$

where, $\chi_{eff}^{(1)}$ is the linear optical susceptibility. Here all system parameters are dimensionless w.r.t Γ_1 and written as,

$\delta_0 = \frac{\delta}{\Gamma_1}$, $\Omega_{10} = \frac{\Omega_1}{\Gamma_1}$, $\Omega_{20} = \frac{\Omega_2}{\Gamma_1}$, $\sigma_{0z}^{(1)} = \frac{\omega_0^{(1)}}{\Gamma_1}$, $\sigma_{0z}^{(2)} = \frac{\omega_0^{(2)}}{\Gamma_1}$, $\beta_0 = \frac{\beta}{\Gamma_1}$, $\Delta_{a0} = \frac{\Delta_a}{\Gamma_1}$, $\omega_{D0} = \frac{\omega_D}{\Gamma_1}$, $\Delta_{d10} = \frac{\Delta_{d1}}{\Gamma_1}$, $\Delta_{d20} = \frac{\Delta_{d2}}{\Gamma_2}$, $\kappa_{d10} = \frac{\kappa_{d1}}{\Gamma_1}$, $\kappa_{d20} = \frac{\kappa_{d2}}{\Gamma_1}$, $M_{z0} = \frac{M_z}{\Gamma_1}$, $E_{p0} = \frac{E_p}{\Gamma_1}$, $G_0 = \frac{G}{\Gamma_1}$, $\omega_{m0} = \frac{\omega_m}{\Gamma_1}$.

III. OPTICAL BISTABILITY

Optical bistability is a quantum phenomenon that displays two output states for the same input state. It has been observed in different optical and optomechanical systems [52–54] and investigated experimentally in semiconductor microcavities [55]. It has received considerable attention due to its promising application in all-optical switching devices [56]. The optomechanical coupling and the third-order Kerr nonlinear medium introduce nonlinearities in our proposed model. Here, we studied the optical response of $N_0 = |a_0|^2$ as a function of dimensionless external pump power E_{p0}. We will discuss how the different system parameters affect optical bistability. All optical switching strongly relies on the demonstration of optical bistability by the system. On gradually increasing the amplitude of the input control (pump) laser, the intracavity steady state photon number N_0 makes a sudden transition from lower stable state (OFF-STATE) to the upper stable state (ON-STATE). On decreasing the control laser power, the system jumps from the ON-STATE to OFF-STATE.

In figure 2(a), such an optical bistability is demonstrated for three different values of the Kerr nonlinearity strength β_0. A higher value of Kerr nonlinearity demonstrates, optical bistability at a higher pump power with a corresponding higher value of N_0. For efficient optical switching, low power consumption and a higher value of N_0 is desirable. Given the results of figure 2(a), we need to choose an optimal value of β_0 such that the system displays optical bistability at a low value of pump power with a moderate value of N_0 which the external detector can detect. Figure 2(b) illustrates optical bistability for different values of dipole-dipole interaction between the two quantum dots (M_{z0}). A higher value of M_{z0} seems desirable since the switching occurs at a relatively low value of the input power with no substantial change in N_0 for different values of M_{z0}. Optical bistability for different values of cavity detuning Δ_{a0} is shown in figure 2(c). It is noted that as Δ_{a0} increases, optical bistability occurs at a higher value of E_{p0} accompanied by a higher intracavity photon number. Thus a moderate value of Δ_{a0} is required for an efficient optical switching as discussed for figure 2(a). The influence of quantum dot detuning Δ_{d10} with a fixed Δ_{d20} is shown in figure 2(d). Optical bistability for a lower value of input pump power is seen to occur for a higher value of Δ_{d10}. No substantial change in N_0 is noticed by changing the Δ_{d10}. Finally figure 2(e) illustrates the influence of optomechanical coupling G_0 on the optical switching response. As noted, a higher value of G_0 leads to optical switching at low values of E_{p0} with a corresponding low value of N_0. Depending upon the sensitivity of the external detector, a moderate value G_0 is required such that detectable value of N_0 and low power consumption is satisfied. In figure 2(f), a plot of $|a_0|^2$ as a function of cavity detuning Δ_{a0} is shown for two different values of optomechanical coupling strength G_0. We see that for a low value of $G_0 = 0.005$, there is a complete absence of bistability (dashed line). For a higher value of $G_0 = 0.01$, the solid line plot displays optical bistability. As G_0 increases further, the bistable behavior becomes more prominent. Thus, we observe the influence of various system parameters on the optical switching characteristics of the system and conclude that a careful choice of these parameters are required to operate the system as an efficient "all-optical switch".

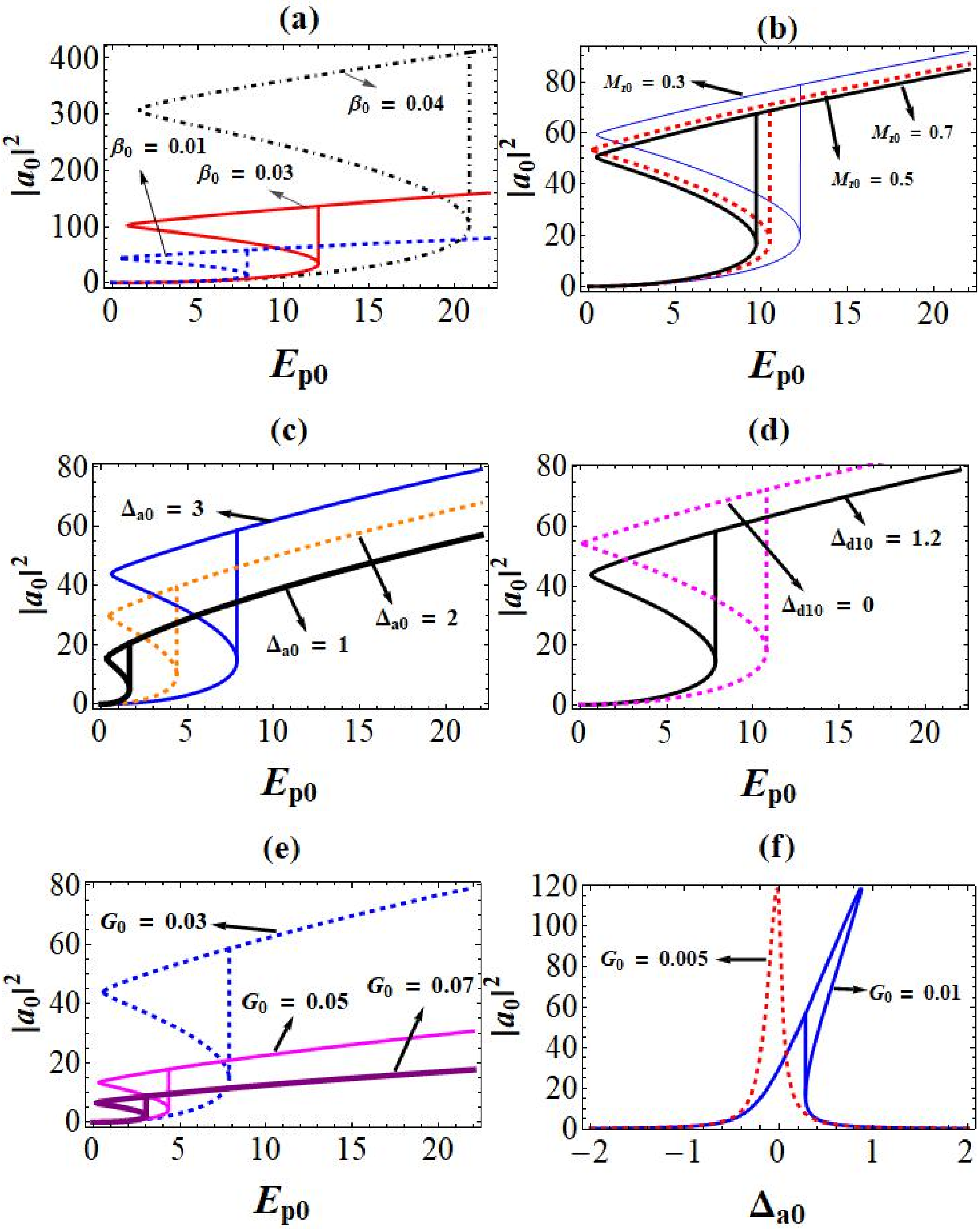

Figure 2: Mean number of photons $|a_0|^2$ as a function of pump field E_{p0} for different values of (a) nonlinear strength (β_0). (b) exciton-exciton dipole interaction (M_{z0}). (c) cavity detuning (Δ_{a0}). (d) first exciton detuning (Δ_{d10}). (e) optomechanical coupling (G_0). (f) Photon intensity $|a_0|^2$ versus cavity detuning Δ_{a0} for different values of optomechanical coupling G_0. Other parameters used are $\Omega_{10} = 0.2$, $\Omega_{20} = 0.2$, $\Delta_{d10} = 1$, $\Delta_{d20} = 1$, $\omega_{D0} = 0.01$, $\kappa_{a0} = 0.1$, $\kappa_{d10} = 0.2$, $\kappa_{d20} = 0.2$, $\omega_{m0} = 0.01$.

IV. PERFORMANCE OF THE OPTICAL SWITCH

With the growing trend of building optical interconnects for short-distance data transfer, optical systems could become a new means of computation rather than just a channel for signal transportation [57]. The nonlinear Kerr effect, caused by a control light changing the refractive index of nonlinear materials and the nonlinear optomechanical effect, is the basis for all-optical switching. As a result, all-optical switching can be considered a key component in developing on-chip ultrafast all-optical switch networks. We now analyze the performance of an optical switch based on the proposed bistable device. The switching ratio is defined as the ratio of maximum to minimum cavity output and is given by,

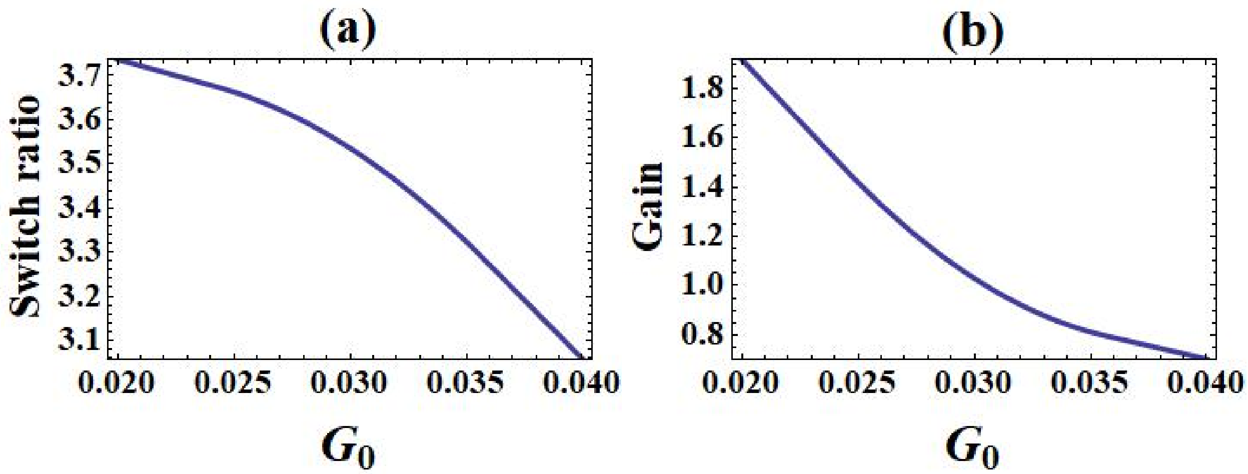

Figure 3: (a)- The graph of Switching ratio as a function of optomechanical interaction strength (G_0). (b)- The graph of gain as a function of optomechanical coupling strength (G_0). All other system parameters are same as used in figure 2.

$$SR = \frac{(P_{out})_{max}}{(P_{out})_{min}}.$$

Here, $P_{out} = < a^{\dagger}a >$. The Gain, G, is defined as,

$$Gain = \frac{(P_{out})_{max} - (P_{out})_{min}}{P_{in}},$$

and $P_{in} = E_{p0}$.

In figure 3(a) and 3(b), we plot the switching ratio (SR) and the gain (G) versus the optomechanical strength G_0 respectively. It is noted that, as the value of G_0 increases, both the switching ratio and the gain decreases. For an efficient optical switching device, both the gain and switching ratio should be large but at the same time power consumption should be less. Keeping in view the result of figure 2(e), we need to choose G_0 in such a way that switching ratio, Gain and power consumption is optimized.

V. ABSORPTION SPECTRUM

In any optical device, tuning and controlling the optical absorption or transmission is important for practical applications. Consequently, we now calculate and plot the linear optical absorption ($\mathrm{Im}[\chi^{(1)}_{eff}]$) as a function of signal-pump detuning δ_0 in realistic experimental parameter domain. Figure 4(a) illustrates the spectral features of $\mathrm{Im}[\chi^{(1)}_{eff}]$ for two different values of β_0 (Kerr nonlinearity). One absorption peak and two transparency dips (negative absorption) are seen in both the plots. We now try to understand the origin of these spectral features using the dressed states of exciton. The sharp transparency dip at $\delta_0 = \omega_{m0} = 2$ is due to mechanically induced three photon resonance. Let us denote $|g, n\rangle$ and $|e, n+1\rangle$ as the lowest dressed level and the highest dressed level of the QD which er are probing. Here n denotes the number states of the mechanical resonator. The electron can make a transition from $|g, n\rangle$ to $|e, n+1\rangle$ by the absorption of two pump photons and emission of a photon at $\omega_p + \omega_m$. This leads to amplification at $\delta_0 = \omega_{m0} = 2$. As seen from figure 4(a), a higher Kerr nonlinearity ($\beta_0 = 0.2$) leads to a transparency dip at $\delta_0 = \omega_{m0}$ with larger amplitude. This is expected since a large β_0 implies more number of two photon process and hence large amplitude signal field. The second broad transparency dip is due to the presence of the second QD. This dip is absent in the case of a single QD [58]. The broad absorption peak centered near $\delta_0 = 0$ is due to optomechanically induced stimulated Rayleigh resonance which corresponds to a transition from $|g, n\rangle$ level to $|e, n+1\rangle$ level. The small negative absorption at $\delta_0 = 0$ is a result of simultaneous absorption of one pump photon (leading toa transition from $|g, n\rangle$ to $|e, n+1\rangle$) and emission of a photon at ω_p into the signal wave.

Figure 4(b) illustrates spectral features for two different values of dipole-dipole interaction M_{z0}. For a higher value of M_{z0}, the transparency dips at $\delta_0 = \omega_{m0}$ and the broad dip has less amplitude compared to that for smaller value of M_{z0}. The absorption peak also has a less amplitude for higher value of M_{z0}. These features are due to the fact that for a relatively stronger dipole-dipole coupling, a significant amount of energy is transferred to

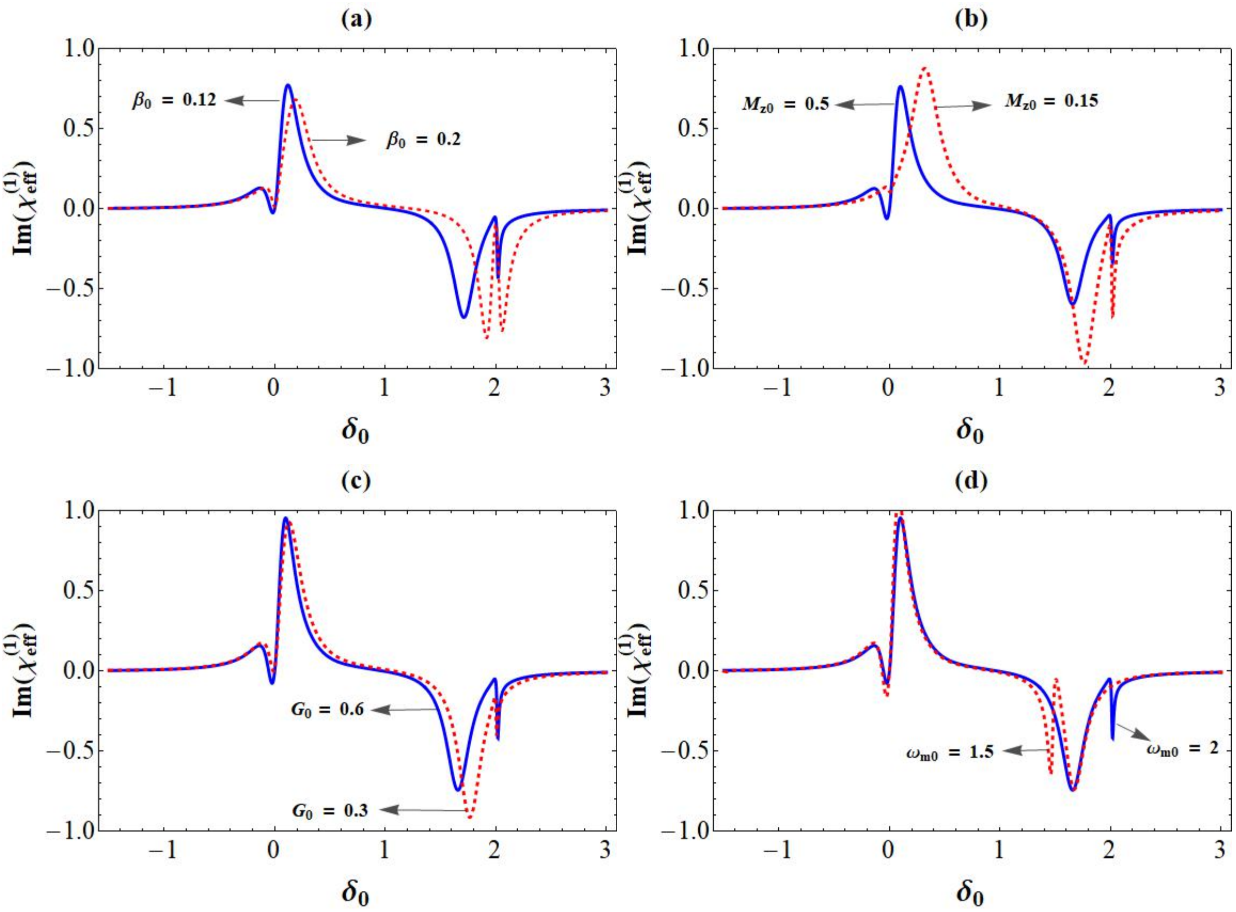

Figure 4: Optical absorption ($\mathrm{Im}[\chi^{(1)}]$) as a function of signal-pump detuning δ_0 for different values of (a) Kerr nonlinear coupling strength (β_0). (b) exciton-exciton dipole interaction (M_{z0}). (c) optomechanical coupling (G_0). (d) mechanical frequency (ω_{m0}). Other parameters used are $\Omega_{10} = 0.5$, $\Omega_{20} = 0.5$, $\Delta_{d20} = 1$, $\omega_{D0} = 0.01$, $\kappa_{a0} = 0.1$, $\kappa_{d10} = 0.2$, $\kappa_{d20} = 0.2$, $E_{p0} = 0.1$.

the second QD which is not probed. Figure 4(c) shows $\mathrm{Im}[\chi^{(1)}_{eff}]$ versus δ_0 for two values of optomechanical coupling G_0. The transparency dip for $\delta_0 = \omega_{m0}$ is extremely small for $G_0 = 0.3$ compared to that for $G_0 = 0.6$. A stronger optomechanical coupling leads to multiple photons being emitted at $\omega_p + \omega_m$ and thus leading to a relatively stronger signal wave. Figure 4(d) illustrates the influence of changing he mechanical frequency ω_{m0} on the optical absorption spectrum. As evident, the sharp transparency dip at $\delta_0 = \omega_{m0}$ shifts from $\delta_0 = 2$ to $\delta_0 = 1.5$ as ω_{m0} changes from $\omega_{m0} = 2$ to $\omega_{m0} = 1.5$ respectively.

VI. CONCLUSION

In summary, we have investigated the nonlinear optical response properties in a double quantum dot optomechanical microcavity, interacting with the photons generated through a third-order nonlinear medium. The steady-state mean-field analysis shows the existence of tunable optical bistability. This property can be used in all-optical switching by tuning the different system parameters. We have also calculated the performance of the optical switch. Based on our mean-field analysis, we have concluded that to develop an efficient optical switching device, the gain switch ratio should be significant, and power consumption should be less. We have also shown that the fluctuation dynamics give rise to negative absorption. We have demonstrated that the fluctuation dynamics give rise to the absorption spectrum, which shows distinct characteristics of negative absorption that can be controlled and tuned by varying various system parameters, thus making our proposed model suitable for the next-generation optoelectronic device.

VII. AUTHOR CONTRIBUTIONS

The theoretical model was proposed by A.B.B and P.K.J. Analytical calculations and plots were done by S.Y and V.B in consultation with A.B.B, P.K.J and S.R. All authors contributed to writing the manuscript and discussing the results. This work forms a part of the PhD thesis of S.Y.

VIII. DISCLOSURE

The authors declare no conflicts of interest.

IX. REFERENCES

---

[1] Kippenberg, T.J., Vahala, K.J.: Cavity optomechanics: back-action at the mesoscale. Science 321, 1172–1176 (2018).

[2] Aspelmeyer, M., Meystre, P., Schwab, K.: Quantum optomechanics. Phys. Today 65, 29–35 (2012).

[3] Mertz, J, Marti, O, Mlynek, J. Appl. Phys. Lett. 1993, 62, 2344.

[4] Hofer, S.G.; Wieczorek, W.; Aspelmeyer, M.; Hammerer, K. Phys. Rev. A 2011, 84, 052327.

[5] Aggarwal, N.; Debnath, K.; Mahajan, S.; Bhattacherjee, A.B.; Mohan, M. Int. J. Quantum Inform. 2014, 12, 1450024.

[6] Loudon, R. Phys. Rev. Lett. 1981, 47, 815.

[7] Wang, Y.D.; Clerk, A.A. Phys. Rev. Lett. 2012, 108, 153603.

[8] Agarwal, G.S.; Huang, S. Phys. Rev. A 2010, 81, 041803.

[9] Tassin, P.; Zhang, L.; Zhao, R.; Jain, A.; Koschny, T.; Soukoulis, C.M. Phys. Rev. Lett. 2012, 109, 187401.

[10] Teufel, J.D.; Donner, T.; Castellanos-Beltran, M.A.; Harlow, J.W.; Lehnert, K.W. Nat. Nanotechnol 2009, 4, 820.

[11] Vahala, K.J.: Optical microcavities. Nature (London) 424, 839–846 (2003).

[12] Hill, J., Safavi-Naeini, A., Chan, J. et al. Coherent optical wavelength conversion via cavity optomechanics. Nat Commun 3, 1196 (2012). https://doi.org/10.1038/ncomms2201.

[13] Yadav, S. and Bhattacherjee, A.B., 2021. Bi-directional photonic switch and optical data storage in a hybrid optomechanical system. Journal of Nonlinear Optical Physics & Materials, p.2250005.

[14] Wang, L., Rastelli, A., Kiravittaya, S., Benyoucef, M. and Schmidt, O.G. (2009), Self-Assembled Quantum Dot Molecules. Adv. Mater., 21: 2601-2618. https://doi.org/10.1002/adma.200803109.

[15] Thomas Unold, Kerstin Mueller, Christoph Lienau, Thomas Elsaesser, and Andreas D. Wieck Phys. Rev. Lett. 94, 137404 2005.

[16] Oliver Gywat, Guido Burkard, and Daniel Loss Phys. Rev. B 65, 205329 2002.

[17] Y. Benny, R. Presman, Y. Kodriano, E. Poem, D. Gershoni, T. A. Truong, and P. M. Petroff Phys. Rev. B 89, 035316 2014.

[18] Gómez, Edgar A, Arteaga, Santiago E, & Vinck-Posada, Herbert. (2017) Momento, (54), 29-39.

[19] Guang-Yin Chen, Neill Lambert, Chung-Hsien Chou, Yueh-Nan Chen, and Franco Nori Phys. Rev. B 84, 045310 2011.

[20] A. Boyer de la Giroday, N. Sköld, R. M. Stevenson, I. Farrer, D. A. Ritchie, and A. J. Shields Phys. Rev. Lett. 106, 216802 2011.

[21] . Kim, D., Carter, S., Greilich, A. et al. Ultrafast optical control of entanglement between two quantum-dot spins. Nature Phys 7, 223–229 (2011). https://doi.org/10.1038/nphys1863.

[22] Z. Wang, S. Zhen, X. Wu, J. Zhu, Z. Cao, and B. Yu, Opt. Commun. 304, 7 (2013).

[23] M. T. Cheng, X. S. Ma, Y. Q. Luo, P. Z. Wang, and G. X. Zhao, Appl. Phys. Lett. 99, 223509 (2011). https://doi.org/10.1063/1.3664637

[24] Y. D. Peng, A. H. Yang, D. H. Li, H. Zhang, Y. P. Niu, and S. Q. Gong, Laser Phys. Lett. 11, 065201 (2014). https://doi.org/10.1088/1612-2011/11/6/065201

[25] S. C. Tian, C. Z. Tong, C. L. Wang, L. J. Wang, H. Wu, E. B. Xing, Y. Q. Ning, and L. J. Wang, Opt. Commun. 312, 296 (2014).

[26] C. H. Yuan and K. D. Zhu, Appl. Phys. Lett. 89, 052115 (2006). https://doi.org/10.1063/1.2335366.

[27] E. Voutsinas, A. F. Terzis, and E. Paspalakis, Phy. Lett. A 378, 219 (2014). https://doi.org/10.1016/j.physleta.2013.10.043

[28] H.M. Gibbs, S.L. McCall, T.N.C. Venkatesan Physical Review Letters, 36 (1976), p. 1135

[29] A. Joshi, M. Xiao Applied Physics B, 79 (2004), p. 65

[30] Fei Zhou, Ye Liu, Zhi-Yuan Li, and Younan Xia, "Analytical model for optical bistability in nonlinear metal nano-antennae involving Kerr materials," Opt. Express 18, 13337-13344 (2010)

[31] M. F. Yanik, S. H. Fan, and M. Soljacic, "High-contrast all-optical bistable switching in photonic crystal microcavities," Appl. Phys. Lett. 83(14), 2739–2741 (2003).

[32] Y. Shen, and G. P. Wang, "Optical bistability in metal gap waveguide nanocavities," Opt. Express 16(12), 8421– 8426 (2008)

[33] G. Priem, P. Dumon, W. Bogaerts, D. Van Thourhout, G. Morthier, and R. Baets, "Optical bistability and pulsating behaviour in silicon-on-insulator ring resonator structures," Opt. Express 13(23), 9623–9628 (2005)

[34] A. Imamoglu, H. Schmidt, G. Woods, and M. Deutsch, Phys. Rev. Lett. 79, 1467 (1997).

[35] Liu, Y., Li, B. and Xiao, Y. (2017) Electromagnetically induced transparency in optical microcavities. Nanophotonics, Vol. 6 (Issue 5), pp. 789-811. https://doi.org/10.1515/nanoph-2016-0168

[36] A. Kasapi, Maneesh Jain, G. Y. Yin, and S. E. Harris Phys. Rev. Lett. 74, 2447 1995

[37] Hennessy, K., Badolato, A., Winger, M. et al. Quantum nature of a strongly coupled single quantum dot–cavity system. Nature 445, 896–899 (2007). https://doi.org/10.1038/nature05586.

[38] Andrei Faraon, Arka Majumdar, Hyochul Kim, Pierre Petroff, and Jelena Vučković Phys. Rev. Lett. 104, 047402 (2010). https://doi.org/10.1103/PhysRevLett.104.047402.

[39] D. Englund, A. Faraon, A. Majumdar, N. Stoltz, P. Petroff, and J. Vučković, "An optical modulator based on a single strongly coupled quantum dot - cavity system in a p-i-n junction," Opt. Express 17, 18651-18658 (2009). https://doi.org/10.1364/OE.17.018651.

[40] S.M. Thon et al., Appl. Phys. Lett. 94, 111115 (2009); https://doi.org/10.1063/1.3103885.

[41] Andrei Faraon et al 2011 New J. Phys. 13 055025.

[42] Xia, J.; Qiao, Q.; Zhou, G.; Chau, F.S.; Zhou, G. Opto-Mechanical Photonic Crystal Cavities for Sensing Application. Appl. Sci. 2020, 10, 7080. https://doi.org/10.3390/app10207080.

[43] Hiroshi Yamaguchi 2017 Semicond. Sci. Technol. 32 103003.

[44] Arka Majumdar, Christopher M. Dodson, Taylor K. Fryett, Alan Zhan, Sonia Buckley, and Dario Gerace ACS Photonics 2015 2 (8), 1160-1166. https://doi.org/10.1021/acsphotonics.5b00214.

[45] Fryett, T., Zhan, A. and Majumdar, A. (2018) Cavity nonlinear optics with layered materials. Nanophotonics, Vol. 7 (Issue 2), pp. 355-370. https://doi.org/10.1515/nanoph-2017-0069.

[46] Janisch, C., Wang, Y., Ma, D. et al. Extraordinary Second Harmonic Generation in Tungsten Disulfide Monolayers. Sci Rep 4, 5530 (2014). https://doi.org/10.1038/srep05530.

[47] Sara Ferretti and Dario Gerace 2012 Phys. Rev. B 85, 033303.

[48] P D Drummond and D F Walls 1980 J. Phys. A: Math. Gen. 13 725.

[49] J. E. Sipe, Navin A. R. Bhat, Philip Chak, and Suresh Pereira 2004 Phys. Rev. E 69, 016604.

[50] Xun-Wei Xu, Yong Li, Ai-Xi Chen, and Yu-xi Liu Phys. Rev. A 93, 023827 (2016). https://doi.org/10.1103/PhysRevA.93.023827.

[51] Boyd, R. W. "Nonlinear Optics, 69–134 Academic Press, Amsterdam, Boston, Heidelberg, London, New York." (2008).

[52] Vengalattore, M.; Hafezi, M.; Lukin, M.D.; Prentiss, M. Phys. Rev. Lett. 2008, 101, 063901.

[53] Jiang C, Liu H, Cui Y, Li X, Chen G and Shuai X 2013 Phys. Rev. A 88 055801

[54] Sete E A and Eleuch H 2012 Phys. Rev. A 85 043824

[55] Bass A, Karr J P, Eleuch H and Giacobino E 2004 Phys. Rev. 69 023809

[56] Sarma B.; Sarma A.K. J. Opt. Soc. Am. B 2016, 33, 1335. doi: 10.1364/JOSAB.33.001335

[57] H. J. Caulfield and S. Dolev, “Why future supercomputing requires optics,” Nature Photonics 4, 261–263 (2014)

[58] Jin-Jin Li and Ka-Di Zhu, Opt. Express 17, 19874-19881 (2009).