Study of Hybrid Optomechanical System containing Multiple Quantum Dots

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ABSTRACT

This research article presents a comprehensive theoretical analysis of a hybrid optomechanical system incorporating N quantum dots (QDs) and a third-order $\chi(3)$ nonlinear medium. The investigation focuses on exploring the impact of varying the number of QDs on the system's bistability and the influence of increased nonlinearity on the power requirements for bistability in optomechanics. Our results indicate that an augmented number of QDs enhances bistability, while higher nonlinearity necessitates greater input power to achieve bistability in the system. Surprisingly, our findings demonstrate that employing a smaller number of QDs yields more efficient switching performance compared to a larger number. The theoretical insights derived from this study offer valuable guidance for advancing the understanding and exploration of optomechanical systems in future research endeavors.

Keywords - Optomechanical; quantum dots; bistability; absorption.

I. INTRODUCTION

Cavity optomechanics has recently become a fast-expanding field at the interface of quantum optics and nanoscience. Numerous studies have been conducted on the optomechanical system's (OMS) characteristics and uses [1-3]. In addition, a fascinating phenomenon known as optical bistability has been researched in several optomechanical systems [4-8] which was experimentally seen in semiconductor microcavities [9]. These systems demonstrate significant nonlinearity attributed to dynamic back action induced by radiation pressure. Applications of these optomechanical systems include their potential use in all-optical switching devices [10-12] and memory storage [13, 14].

Conversely, the coherent interaction between a single semiconductor quantum dot (QD) exciton and the optical mode of a microcavity has been thoroughly investigated in cavity quantum electrodynamics (cQED) experiments [15–18] and theoretical studies [19–21]. Recent advancements in technology are making it increasingly feasible to experimentally achieve the strong coupling of multiple quantum dots to the microcavity mode [22–26]. The progress in the design and control of complex multiple quantum dots [27, 28] is contributing to the realization of this possibility [29, 30]. A traditional approach to solving the situation with several quantum dots is described in ref. [31]. According to earlier studies, OB may be observed using just one QD [32, 33] when the QD is directly stimulated or pumped by an external laser, causing the system to enter bistability. We do not directly pump the QDs into our system. A Kerr nonlinear medium is also additionally placed within the cavity. When a $\chi^{(3)}$ medium is positioned inside a cavity, a lot of photons are created. There is a considerable nonlinear interaction between photons as a result of the $\chi^{(3)}$ medium. Additionally, a different investigation into the bistability of coupled double quantum dot systems (CDQDs) [34, 35] discovered that the cavity field is bistable for high levels of cavity-dot coupling. The goal of this work is to compute bistability, and then it should be feasible to modify it by altering system parameters in order to improve switching performance.

The work in cavity optomechanics and quantum dot-microcavity interactions holds promise for all-optical switching devices, memory storage, and quantum information processing. Bridging quantum optics and nanoscience, it advances interdisciplinary research, unveils fundamental principles, and fuels technological innovation. Manipulating bistability enhances device performance, while strong coupling of quantum dots offers quantum enhancements. This work's significance lies in its potential to reshape communication, computation, and technology landscapes.

II. MODEL AND HAMILTONIAN

Figure 1 depicts the paradigm we covered in this paper. To construct the microcavity, a sequence of Distributed Bragg mirrors (DBR) is utilized. These DBR techniques effectively confine light both longitudinally and transversely [36]. The initial and final layers of the structure consist of AlGaAs, chosen due to its refractive index, which lies midway between that of GaAs and air. Mechanical resonators based on GaAs are fabricated using conventional micromachining techniques involving selective etching [37, 38]. This property enhances the coupling of light into and out of the structure. Between the cavity is a two -level QD system ensemble. As a bonus, the cavity contains a nonlinear $\chi^{(3)}$ medium, which interacts with the QD ensemble by generating photons.

By employing well-established techniques, a $\chi^{(3)}$ nonlinear 2D layered medium is fabricated within the photonic crystal cavity [39–42]. Atomically thin, two-dimensional materials possess unique physical properties, including substantial second- and third-order optical nonlinearities [39, 40]. These materials can be readily transferred to an existing device, such as a photonic crystal cavity composed of distributed Bragg reflectors [40], using a straightforward chemical vapor deposition technique on a medium like silicon dioxide. The transfer of these 2D materials onto a pre-constructed cavity allows for independent growth of the 2D material, eliminating the need for reliance on the etching procedure during fabrication. Unlike molecular beam epitaxy, this procedure does not require lattice matching between the device and the 2D material [39]. Graphene, MoS2, and GaSe are among the experimentally established 2D layered materials known for their third-order nonlinear characteristics [40].

To create a microcavity, defects in the form of point or line defects are typically introduced into the periodic structure of the cavities, and these defects are then utilized for fabricating Photonic Crystal (PhC) cavities. The periodic dielectric structures that constitute the periodic structure are characterized by a periodic variation in the dielectric constant [43]. To form the optomechanical system, photons are directed and concentrated into the air-slot situated between two flexibles, hanging membranes [44]. Conversely, the construction of GaAs/AlGaAs-based mechanical resonators entails the application of micromachining and selective etching techniques. Thin-film crystal growth techniques are employed to create a larger structure, with a sacrificial layer formed underneath the resonator. Subsequently, the sacrificial layer is meticulously removed to separate the structure from the substrate [37].

In the rotating-wave approximation, the interaction Hamiltonian of the entire system, which consists of the quantum-dot ensemble and the $\chi^{(3)}$ medium is given as,

$$H = \sum_{i=1}^{N}[\Delta_{d_i}\sigma_+^i\sigma_-^i + \Omega_i(a^+\sigma_-^i + a\sigma_+^i)] + \Delta_c a^+a + \frac{\omega_m}{2}(p^2+q^2) + \varepsilon_p(a^+ + a) + \lambda(a^+e^{-i\delta t} + ae^{i\delta t}) - Ga^+aq + \alpha a^+a^+aa. \quad (1)$$

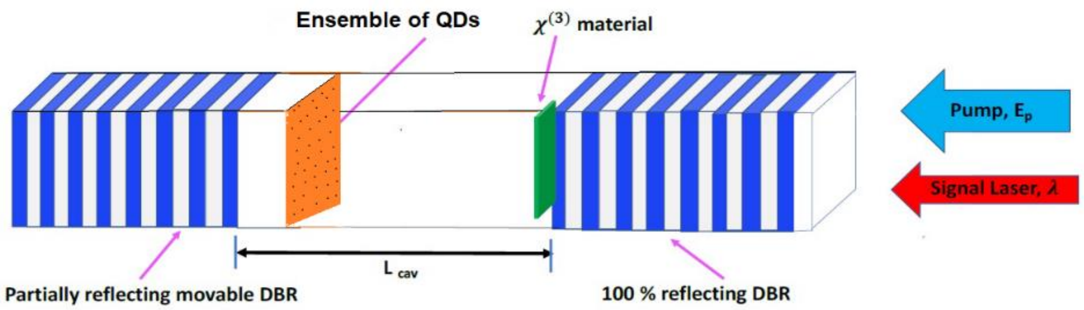

Figure 1: The system, which consists of an ensemble of N quantum dots that are strongly linked inside the cavity, is shown schematically. Cavity mode is generated by DBR mirrors.

The first term of the above Hamiltonian denotes the energy of QDs. Second term shows the interaction between cavity and dots. Third term shows the energy of the cavity mode. Fourth term is energy for the harmonic oscillator. Fifth and sixth term shows the interaction of pump laser and probe laser with cavity mode respectively. Seventh term shows the optomechanical coupling. The last term shows the Kerr nonlinear interaction with cavity photons.

The system's behavior, which is derived from Equation (1), can be characterized using the following Langevin equations,

$$\dot{a} = -i\Delta_c a - \sum_{i=1}^{N} i\Omega_i\sigma_-^{(i)} - k_c a + iGaq - 2i\alpha|a|^2 a - i\varepsilon_p - i\lambda e^{-i\delta_0 t} + a_{in}(t) \quad (2)$$

$$\dot{\sigma}_-^{(i)} = \sum_{i=1}^{N} -i\Delta_{d_i}\sigma_-^{(i)} - k_{d_i}\sigma_-^{(i)} - \sum_{i=1}^{N} i\Omega_i a\sigma_z^{(i)} + \sigma_{-in}^{(i)}(t) \quad (3)$$

$$\dot{q} = \omega_m p \quad (4)$$

$$\dot{p} = -\omega_m q + Ga^\dagger a - \gamma_m p + \zeta(t) \quad (5)$$

Here, $a_{in}(t), \sigma_{-in}^{(i)}(t)$ and $\zeta(t)$ are the input noise operators for cavity mode, ith mode of QDs and mechanical mode, respectively with zero mean $< a_{in}(t) > = < \sigma_{-in}^{(i)}(t) > = <\zeta(t) > = 0$. The decay rates for the operators of the cavity, quantum dot, and mechanical oscillator are denoted as k_c, k_d, and , γ_m respectively.

III. RESULTS AND DISCUSSION

The research presented in this article delves into a comprehensive analysis of a novel hybrid optomechanical system, where, the system incorporates a collection of N quantum dots (QDs) and incorporates the influence of a third-order $\chi(3)$ nonlinear medium. The primary objective of this investigation is to shed light on the intricate behavior of bistability within this complex system. Bistability, a phenomenon where a system possesses two stable states for a given input, has garnered significant interest due to its potential applications in all-optical switching and memory storage.

Solving the Hamiltonian described above in the steady-state condition, we get the bistability.

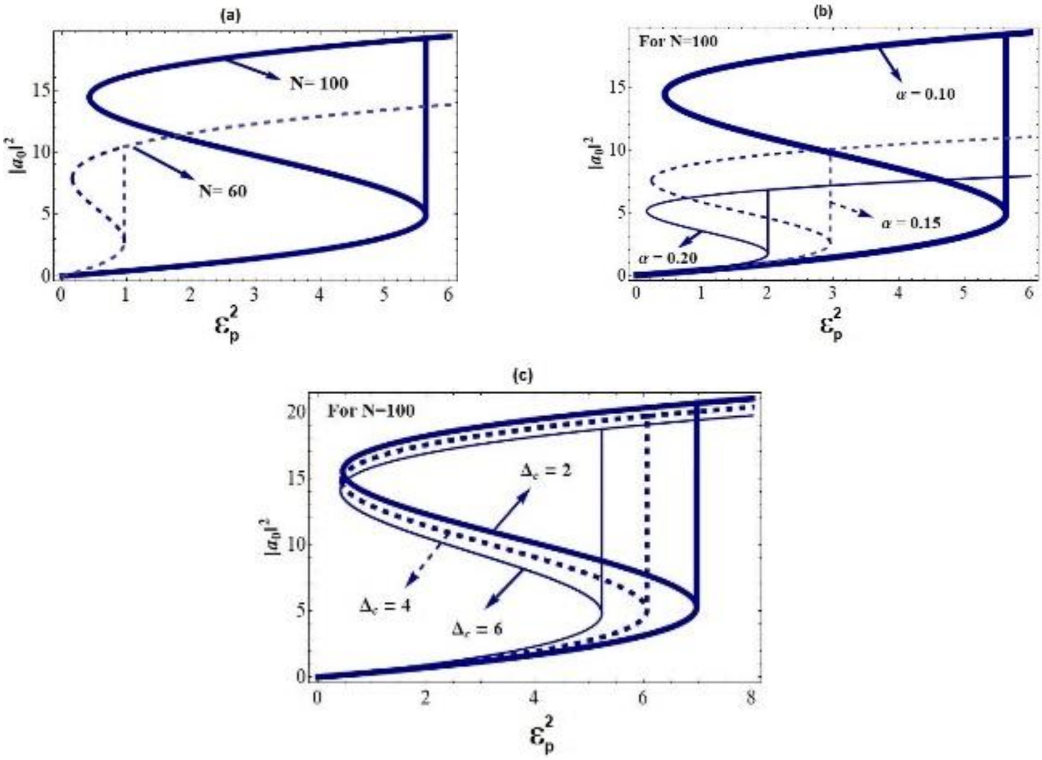

Figure 2: The number of photons as a function of input pump power. (a)- For different number of QDs. (b)- For different values of kerr-nonlinear strength with fix N=100. (c)- For different values of cavity detuning with fix N=100.

Figure 2(a) illustrates bistable behaviour in the quantity of photons as a function of input pump power. (With N = 100 and 60) (i.e., number of QDs). We see that the bistability window shrinks as the number of QDs decreases. The shrinking bistability window as the number of QDs decreases (from 100 to 60) suggests that the presence of more QDs enhances the bistability behavior. This implies that the collective interactions among a larger number of QDs have a stabilizing effect on the system, allowing for a broader range of input pump power to exhibit bistability. Figure 2(b) demonstrates that increasing the third-order nonlinear medium strength (α) reduces the number of photons and the pump power range for bistability. This indicates that a stronger nonlinear medium leads to a more pronounced nonlinear response, causing a decrease in photon number and a shift of the bistability region to lower pump power levels. In figure 2(c), for fix N=100, we observe that the input field strength for which bistability occurs shifts towards a lower value as the value of Δ_c is increased. This suggests that tuning the detuning can control the sensitivity of the system to input power changes and influence the conditions for bistability. In order to achieve optical bistability with a reasonable value for $|a_0|^2$, we must choose an optimal value for α and Δ_c. This implies that a careful balance between these parameters is necessary to achieve desirable bistable behavior while maintaining appropriate input power levels.

As a result, we are able to understand how various system parameters impact the system's optical switching characteristics and infer that careful attention to these factors is necessary for the system to effectively serve as a "all-optical switch".

IV. CONCLUSION

In conclusion, this research article presents a theoretical investigation of a hybrid optomechanical system, featuring N quantum dots (QDs) and a third-order $\chi(3)$ nonlinear medium. The study reveals that increasing the number of QDs enhances bistability, and higher nonlinearity requires higher input power for bistability to occur in optomechanics. The unexpected result of the impact of the number of QDs on bistability challenges conventional assumptions, highlighting that a larger number of QDs does not necessarily lead to enhanced bistable behavior. This finding underscores the complexity of these systems and emphasizes the importance of thoughtful optimization for optimal performance. Furthermore, the study's elucidation of the relationship between nonlinearity and input power sheds light on the delicate balance required to achieve bistability. Understanding how increased nonlinearity influences the power requirements provides crucial guidance for designing systems that exhibit the desired bistable behavior. The insights derived from this research not only deepen our understanding of optomechanical systems but also provide a roadmap for future investigations in this burgeoning field. The findings from this study mark a pivotal step towards harnessing the potential of these hybrid systems and underscore the rich opportunities that lie ahead in this evolving frontier of research.

REFERENCES

[1] H. Foroughi and N. Daneshfar, The European Physical Journal D, **77,** 118 (2023).
[2] B. Chen, X.F. Wang, J.K. Yan, X.F. Zhu, C. Jiang, Superlattices Microstruct. **113**, 301 (2018)
[3] J. Kippenberg and K. J. Vahala, "Cavity opto-mechanics," Opt. Express **15**, 17172–17205 (2007).
[4] S. Zhang, J. Li, R. Yu, W. Wang, Y. Wu, Sci. Rep. **7**, 39781 (2017).
[5] K. Ullah, Chin. Phys. B **28**, 114209 (2019)
[6] B. Sarma and A. K. Sarma J. Opt. Soc. Am. B **33** 7 (2016).
[7] V. Bhatt, Sabur A. Barbhuiya, Pradip K. Jha and Aranya B. Bhattacherjee, J. Phys. B: At. Mol. Opt. Phys. **53** 155402 (2020).
[8] V. Bhatt, Surabhi Yadav, Pradip K. Jha and Aranya B. Bhattacherjee, J. Phys.: Condens. Matter **33** 365302 (7pp) (2021)
[9] A. Bass, J. P. Karr, H. Eleuch and E. Giacobino Phys. Rev. **69** 023809 (2004).
[10] C. Jiang, H. Liu, Y. Cui, X. Li, G. Chen, X. Shuai, Phys. Rev. A **88,** 055801 (2013).
[11] E. A. Sete, H. Eleuch, Phys. Rev. A, **85**, 043824 (2012).
[12] B. Sarma, A. K. Sarma, J. Opt. Soc. Am. B, **33**, 7 (2016).
[13] D. Yan, Z. H. Wang, C. N. Ren, H. Gao, Y. Li, J. H. Wu, Phys. Rev. A, **91**, 023813 (2015).
[14] M. Gao, F. C. Lei, C. G. Du, G. L. Long, Phys. Rev. A, **91**, 013833 (2015).
[15] T. Yoshie, A. Scherer, J. Heindrickson, G. Khitrova, H. M. Gibbs, G. Rupper, C. Ell, O. B. Shchekin, D. G. Deppe, Nature, 432, 200 (2004).
[16] J. P. Reithmaier, G. Sek, A. Loffler, C. Hofmann, S. Kuhn, S. Reitzen- stein, L. V. Keldysh, V. D. Kulakovskii, T. L. Reinecker, A. Forchel, Nature, 432, 197 (2004).
[17] E. Peter, P. Senellart, D. Martrou, A. Lemaitre, J. Hours, J. M. Gerard, J. Bloch, Phys. Rev. Lett., 95, 067401 (2005).
[18] S. Reitzenstein, A. Loffler, C. Hofmann, A. Kubanek, M. Kamp, J. P. Reithmaier, A. Forchel, V. D. Kulakovskii, L. V. Keldysh, I. V. Pono- marev, T. L. Reinecke, Opt. Lett., 31, 1738 (2006).
[19] L. C. Andreani, G. Panzarini, J.-M. Gerard, Phys. Rev. B, 60, 13276 (1999).
[20] G. Cui, M. G. Raymer, Phys. Rev. A, 73, 053807 (2006).
[21] F. P. Laussy, E. del Valle, C. Tejedor, Phys. Rev. Lett. 2008, 101, 083601.
[22] A. N. Poddubny, M. M. Glazov, N. S. Averkiev, Phys. Rev. B 2010, 82, 205330.
[23] G. Yeoman, G. M. Meyer, Phys. Rev. A 1998, 58, 2518.
[24] S. Strauf, K. Hennessy, M. T. Rakher, Y. S. Choi, A. Badolato, L. C. Andreani, E. L. Hu, P. M. Petroff, D. Bouwmeester, Phys. Rev. Lett. 2006, 96, 127404.
[25] X. Li, X. Wang, Z. Wu, W.-X. Yang, A. Chen, Phys. Rev. B 2021, 104, 224434.
[26] J. Naikoo, K. Thapliyal, A. Pathak, S. Banerjee, Phys. Rev. A 2018, 97, 063840.
[27] S. Kiravittaya, A. Rastelli, O. G. Schmidt, Rep. Prog. Phys. 2009, 72, 046502.
[28] H. Kim, S. M. Thon, P. M. Petroff, D. Bouwmeester, Appl. Phys. Lett. 2009, 95, 243107.
[29] E. Gallardo, L. J. Martinez, A. K. Nowak, D. Sarkar, H. P. van der Meulen, J. M. Calleja, C. Tejedor, I. Prieto, D. Granados, A. G. Taboada, J. M. García, P. A. Postigo, Phys. Rev. B 2010, 81, 193301.
[30] H. Kim, D. Sridharan, T. C. Shen, G. S. Solomon, E. Waks, Opt. Ex- press 2011, 19, 2589.
[31] Y. Peng, Z. Yu, Y. Liu, W. Zhang, H. Ye, Optics communications **324**, 172-177 (2014).
[32] J. Li, R. Yu, J. Liu, P. Huang, and X. Yang, Physica E **41**, 70 (2008).
[33] A. Majumdar et.al., Proceedings of SPIE - The International Society for Optical Engineering 7611 (2010)
[34] A. Mitra and R. Vyas Phys. Rev. A **81**, 012329 (2010)
[35] V. Bhatt, S. Yadav, Pradip K. Jha and Aranya B. Bhattacherjee, Photonics and Nanostructures - Fundamentals and Applications **51**(4) (2022) 101043.
[36] J. Gudat, Cavity Quantum Electrodynamics with Quantum Dots in Microcavities, PhD Thesis, University of Leiden 2012.
[37] H. Yamaguchi, Semicond. Sci. Technol. 2017, **32**, 103003.
[38] H. R. Bohm, S. Gigana, F. Blaser, A. Zeilinger, M. Aspelmeyer, Appl. Phys. Letts. 2006, **89**, 223101.
[39] A. Majumdar, C. M. Dodson, T. K. Fryett, A. Zhan, S. Buckley, D. Gerace, ACS Photonics 2015, **2**, 1160.
[40] T. Fryett, A. Zhan, A. Majumdar, Nanophotonics 2018, 7, 355.
[41] C. Janisch, Y. Wang, D. Ma, N. Mehta, A. L. Elías, N. P. López, M. Terrones, V. Crespi, Z. Liu, Sci. Rep. 2014, **4**, 5530.
[42] A. A. Ahmadi, Quantum Dots - A Variety of New Applications, InTech Publication, Croatia 2012.
[43] X. Ji, Q. Qiao, G. Zhou, F. S. Chau, G. Zhou, Appl. Sci. 2020, **10**, 7080.
[44] A. H. Safavi-Naeini, T. P. M. Alegre, M. Winger, O. Painter, Appl. Phys. Lett. 2010, **97**, 181106.