materials proceedings

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Proceeding Paper

Optical Transparency near a MoS_2 Nanodisk †

Nikos Iliopoulos [1], Ioannis Thanopulos [1], Vasilios Karanikolas [2] and Emmanuel Paspalakis [1,*]

1 Materials Science Department, School of Natural Sciences, University of Patras, 265 04 Patras, Greece; n.iliopoulos@windowslive.com (N.I.); ithano@upatras.gr (I.T.)
2 International Center for Young Scientists (ICYS), National Institute for Materials Science (NIMS), 1-1 Namiki, Tsukuba, Ibaraki 305-0044, Japan; karanikolas.vasileios@nims.go.jp
* Correspondence: paspalak@upatras.gr
† Presented at the 3rd International Online-Conference on Nanomaterials, 25 April–10 May 2022; Available online: https://iocn2022.sciforum.net/.

Abstract: It has recently been shown that the molybdenum disulfide (MoS_2) nanodisk leads to sharp and high peaks in the Purcell enhancement factor of a quantum emitter nearby the nanodisk, leading to strong light–matter coupling with nearby quantum systems. In this work, we show that the strong coupling at the nanoscale can lead to vacuum-induced transparency. For example, we study the case where a three-level quantum system is placed near an MoS_2 nanodisk. We find that we may obtain either single or multiple vacuum-induced transparency effects, depending on the distance between the quantum system and the MoS_2 nanodisk and the resonance energy of the quantum system.

Keywords: vacuum-induced transparency; electromagnetically induced transparency; three-level quantum system; MoS_2 nanodisk; strong coupling; Purcell effect

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Citation: Iliopoulos, N.; Thanopulos, I.; Karanikolas, V.; Paspalakis, E. Optical Transparency near a MoS_2 Nanodisk. *Mater. Proc.* **2022**, *9*, 18. https://doi.org/10.3390/materproc2022009018

Academic Editor: Antonio Di Bartolomeo

Published: 24 April 2022

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1. Introduction

Electromagnetically induced transparency is an important quantum coherence and interference phenomenon in optical and photonic structures [1]. The typical system for electromagnetically induced transparency involves a three-level, Λ-type, quantum system that coherently interacts with two electromagnetic fields, a weak probe field and a strong coupling field, which individually drive the two allowed electronic transitions of the quantum system. The presence of the coupling field leads to the optical transparency of the probe field, which couples the adjacent transition in the quantum system. An interesting alternative of electromagnetically induced transparency is vacuum-induced transparency, where the external coupling field is replaced by strong coupling with a modified cavity vacuum [2]. Vacuum-induced transparency has been experimentally realized for atoms in an optical cavity, and has been predicted to occur for quantum systems embedded in other photonic structures such as, for example, photonic crystals [3], polaritonic–photonic crystal nanofibers [4], and metamaterials [5].

Here, we show that the strong coupling at the nanoscale which can occur when a quantum system is placed near a photonic nanostructure and can also lead to vacuum-induced transparency. As an example, we studied the case where a three-level quantum system is placed near a MoS_2 nanodisk. It has recently been shown that the localized exciton–polariton modes occurring in the MoS_2 nanodisk lead to sharp and high peaks in the Purcell enhancement factor spectrum, leading to strong light–matter coupling with nearby quantum systems [6–9]. In this work, we show that this effect also leads to vacuum-induced transparency in a three-level quantum placed near the MoS_2 nanodisk, when the resonance energy of the quantum system is near an exciton–polariton resonance of the MoS_2 nanodisk. We also find that we may obtain either single or multiple vacuum-induced transparency effects depending on the distance between the quantum system and the MoS_2 nanodisk and the value of the resonance energy of the quantum system.

2. Theory

We consider a three-level Λ-type quantum system at distance a D from the surface of a MoS_2 nanodisk with radius R, as shown in Figure 1. A probe laser field with energy ω_L interacts with the transition $|3\rangle \leftrightarrow |2\rangle$, while the transition $|2\rangle \leftrightarrow |1\rangle$ is nearly resonant with a surface exciton–polariton mode of the MoS_2 nanodisk. Here, ω_0 is the energy of the $|2\rangle \leftrightarrow |1\rangle$ transition, which we call resonance energy. We take the origin of the coordinate system to coincide with the center of the nanodisk and the quantum system lies on the z axis of the coordinate system. For the theoretical description, we use a macroscopic quantum electrodynamics approach [7,10], where the probability amplitude approach for the quantum dynamics is combined with classical electromagnetic computations for the calculation of the electromagnetic Green's tensor.

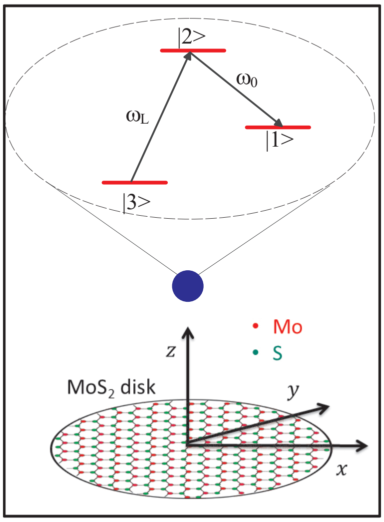

Figure 1. The Λ-type three-level quantum system placed at a distance z perpendicular from the center of a MoS_2 nanodisk of radius R.

Specifically, we obtain the evolution of the probability amplitudes for the three-level Λ-type quantum system under the influence of the MoS_2 nanodisk, extending the work of ref. [7], apply the rotating wave approximation, and properly adapt the methodology of ref. [3] for deriving the linear electric susceptibility of the quantum system, χ. We find that the linear susceptibility crucially depends on the directional Purcell factor of the quantum system near the MoS_2 nanodisk, which is calculated from the electromagnetic Green's tensor, using the approach presented in refs. [6,7].

3. Results and Discussion

In Figure 2, we present the Purcell factor of a quantum emitter at distances of $D = 5$ nm and $D = 15$ nm from a MoS_2 nanodisk along the parallel, x, in the direction of the nanodisk. The nanodisk has a radius $R = 30$ nm. The Purcell factor shows intense and narrow peaks at both distances, an indication that the present system can lead to strong light–matter coupling. As the distance between the quantum system and the MoS_2 nanodisk becomes shorter, the number of peaks in the Purcell factor increases and the peaks become stronger.

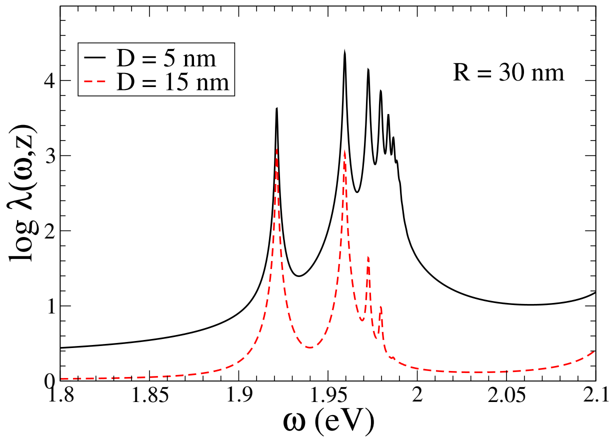

Figure 2. Purcell factor of a quantum emitter at $D = 5$ nm and $D = 15$ nm from a 30 nm radius MoS_2 nanodisk, with the electric dipole along the x direction.

We then use the results of the Purcell factor shown in Figure 2 and calculate the linear absorption and dispersion spectra, as a function of the detuning $\delta = \omega_L - \omega_{23}$, of the quantum system from the imaginary and real parts of the electric susceptibility χ, respectively, obtained with the approach described in the previous section. Here, ω_{23} is the energy of the $|2\rangle \leftrightarrow |3\rangle$ transition. The quantum system is placed at a distance of $D = 15$ nm from the center of the MoS_2 nanodisk. The results of the absorption and dispersion spectrum for a quantum system with a resonance energy of $\omega_0 = 1.921$ eV is shown in Figure 3. The resonance energy $\omega_0 = 1.921$ eV corresponds to the first peak of the red curve in Figure 2. Of course, in the absence of the MoS_2 disk, the absorption and dispersion spectrum has the usual Lorentzian form for the absorption spectrum and showing the typical dispersion with anomalous dispersion near the resonance (not shown here) [1,2]. The behavior shown in Fig. 3 is markedly different. The absorption has two strong peaks and shows strong suppression between the peaks. This is the vacuum-induced transparency effect, which turns the otherwise opaque quantum medium transparent without the need for an external coherent driving field. Here, the vacuum-induced transparency occurs due to the strong interaction of the spontaneously emitted photons of the quantum system with the modified vacuum due to the presence of the MoS_2 nanodisk. Furthermore, the dispersion spectrum shows a positive slope near resonance and its value indicates that slow light is possible in the system.

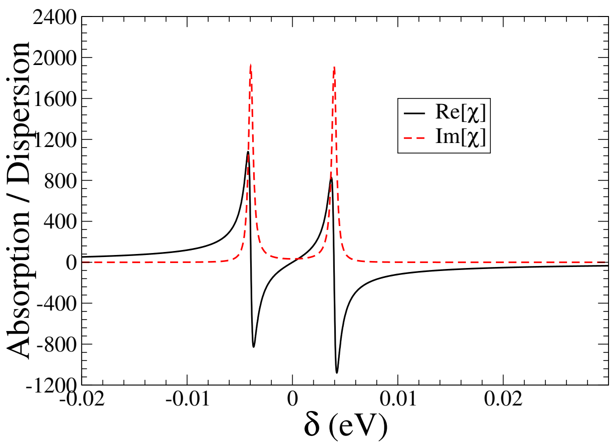

Figure 3. (color online) Absorption and dispersion spectra as a function of the detuning δ for a quantum system with resonance energy $\omega_0 = 1.921$ eV located at distance $D = 15$ nm from a MoS_2 nanodisk of radius $R = 30$ nm.

We also present results for the linear absorption and dispersion spectra as a function of the detuning δ for a quantum system with a resonance energy of $\omega_0 = 1.956$ eV in Figure 4. The quantum system in this case is placed at a distance of $D = 5$ nm from the center of the MoS_2 nanodisk. The resonance energy $\omega_0 = 1.956$ eV corresponds to the second peak of the black curve in Figure 2. The behavior shown in Figure 4 is different from that shown in Figure 3. Vacuum-induced transparency effects appear in this system too, and the spectra seem similar to that of Figure 3 if one looks at the main panel only, which shows the negative values of the detuning, but the actual spectra have multiple peaks and dips, as one may notice from the inset which shows the continuation of the spectra for positive detuning values. Thus, multiple vacuum-induced transparency effects also appear in this system simply by changing the distance of the quantum system from the MoS_2 nanodisk, if the resonance energy is such that the interaction of the quantum system with the modified vacuum is influenced by multiple peaks of the Purcell factor.

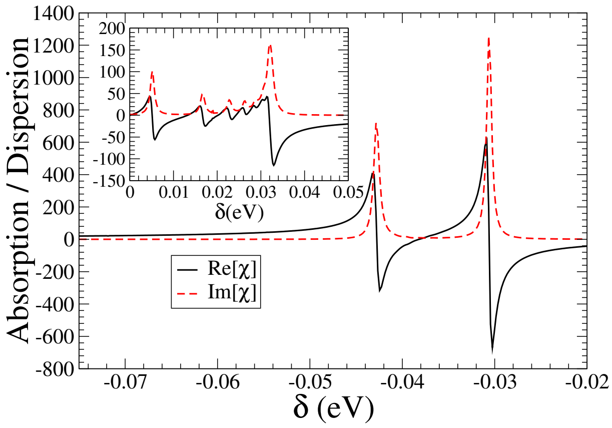

Figure 4. (color online) Absorption and dispersion spectra as a function of the detuning δ for a quantum system with a resonance energy $\omega_0 = 1.956$ eV located at distance $D = 5$ nm from a MoS_2 nanodisk of radius $R = 30$ nm.

4. Summary

Recently, it has been shown that an MoS_2 nanodisk leads to sharp and high peaks in the Purcell enhancement factor of a quantum emitter nearby the nanodisk, and this leads to strong light-matter coupling with nearby quantum systems. Here, we showed that this strong coupling at the nanoscale can lead to vacuum-induced transparency when a three-level quantum system is placed near a MoS_2 nanodisk and also has resonance energy close to an exciton–polariton resonance of the MoS_2 nanodisk. We found that depending on the distance of the quantum system from the MoS_2 nanodisk and the resonance energy of the quantum system, we may either obtain single or multiple vacuum-induced transparency effects.

Author Contributions: Conceptualization, E.P.; methodology, N.I., I.T., V.K. and E.P.; software, N.I., I.T. and V.K.; validation, I.T. and E.P.; investigation, N.I., I.T., V.K. and E.P.; data curation, N.I., I.T. and V.K.; writing—original draft preparation, N.I., I.T., V.K. and E.P.; writing—review and editing, N.I., I.T., V.K. and E.P.; visualization, I.T.; supervision, I.T. and E.P. All authors have read and agreed to the published version of the manuscript.

Funding: This research received no external funding.

Institutional Review Board Statement: Not applicable.

Informed Consent Statement: Not applicable.

Data Availability Statement: The data presented in this study are available on request from the corresponding author.

Conflicts of Interest: The authors declare no conflict of interest.

References

1. Fleischhauer, M.; Imamoglu, A.; Marangos, J.P. Electromagnetically induced transparency: Optics in coherent media. *Rev. Mod. Phys.* **2005**, *77*, 633–673. [CrossRef]
2. Tanji-Suzuki, H.; Chen, W.; Landig, R.; Simon, J.; Vuletić, V. Vacuum-induced transparency. *Science* **2011**, *333*, 1266–1269. [CrossRef] [PubMed]
3. Paspalakis, E.; Kylstra, N.J.; Knight, P.L. Transparency near a photonic band edge. *Phys. Rev. A* **1999**, *60*, R33–R36 . [CrossRef]
4. Cox, J.D.; Singh, M.R.; Racknor, C.; Agarwal, R. Switching in polaritonic–photonic crystal nanofibers doped with quantum dots. *Nano Lett.* **2011**, *11*, 5284–5289. [CrossRef] [PubMed]
5. Fan, J.W.; Xu, J.-P.; Cheng, M.-T.; Yang, Y.-P. Vacuum induced transparency in metamaterials. *Opt. Express* **2018**, *26*, 19498–19512. [CrossRef] [PubMed]
6. Karanikolas, V.D.; Paspalakis, E. Localized exciton modes and high quantum efficiency of a quantum emitter close to a MoS_2 nanodisk. *Phys. Rev. B* **2017**, *96*, 041404(R). [CrossRef]
7. Thanopulos, I.; Karanikolas, V.; Iliopoulos, N.; Paspalakis, E. Non-Markovian spontaneous emission dynamics of a quantum emitter near a MoS_2 nanodisk. *Phys. Rev. B* **2019**, *99*, 195412. [CrossRef]
8. Thanopulos, I.; Karanikolas, V.; Paspalakis, E. Non-Markovian spontaneous emission interference near a MoS_2 nanodisk. *Opt. Lett.* **2019**, *44*, 3510–3513. [CrossRef]
9. Iliopoulos, N.; Karanikolas, V.; Thanopulos, I.; Paspalakis, E. Entanglement dynamics for quantum emitters strongly coupled with molybdenum disulfide nanodisks, *Phys.-Low-Dimens. Syst. Nanostruct.* **2020**, *119*, 113967. [CrossRef]
10. Dung, H.T.; Knöll, L.; Welsch, D.-G. Spontaneous decay in the presence of dispersing and absorbing bodies: General theory and application to a spherical cavity. *Phys. Rev. A* **2000**, *62*, 053804. [CrossRef]