Multistability and high reflectance of a monolayer of three-level quantum emitters with a doublet in the excited state

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Abstract. We study theoretically the nonlinear optical response of a monolayer of three-level quantum emitters with a doublet in the excited state. It is shown that the layer’s response exhibits multistability. In a certain frequency range, the monolayer operates as a perfect bistable mirror.

We conduct a theoretical study of the steady-state optical response of a monolayer of regularly spaced three-level quantum emitters (QEs) with a doublet in the excited state. The total (retarded) dipole-dipole interaction of QEs is taken into account. This interaction provides a positive feedback. The interplay of the latter and the immanent nonlinearity of QE’s gives rise to a multistability of the monolayer optical response. In a certain frequency range, the system operates as a nanometric bistable mirror.

It is assumed that the monolayer undergoes an action of a CW external field of a Rabi amplitude \( \Omega_0 \) and frequency \( \omega_0 \), which is quasi-resonant with the QE’s allowed transitions. A constituent QE is modelled by a three-level V-type quantum system with the ground state \( |1\rangle \), and a doublet \( |2\rangle \) and \( |3\rangle \) in the excited states. The allowed optical transitions are \( |1\rangle \leftrightarrow |2\rangle \) and \( |1\rangle \leftrightarrow |3\rangle \). They are characterized by the transition dipole moments \( d_{21} \) and \( d_{31} \), transition frequencies \( \omega_{21} \) and \( \omega_{31} \), and spontaneous decay constants \( \gamma_{21} \) and \( \gamma_{31} \). The doublet is described by the splitting \( \Delta_{32} \) and the relaxation constant \( \gamma_{32} \).

The optical dynamics of a constituent QE is governed by the 3x3 density matrix \( \rho_{\alpha\beta} \) (\( \alpha, \beta = 1,2,3 \)). The total field \( \Omega \) acting on a given QE in the monolayer represents a sum of the external field \( \Omega_0 \) and the field produced by all others QEs in place of the given one. In this way, the total (retarded) QE-QE dipole-dipole interaction is taken into account. The near-zone (far-zone) part of the QE-QE interaction gives rise to a dynamic renormalization of the transition frequencies \( \omega_{21} \) and \( \omega_{32} \) (relaxation constants \( \gamma_{21} \) and \( \gamma_{31} \)), depending on the population difference of corresponding transitions \([1,2] \). The effects are described by the constants \( \Delta_1 \) (shift) and \( \gamma_R \) (relaxation). These parameters govern a positive feedback which is responsible for a sophisticated nonlinear optical properties of the monolayer.

In Fig. 1, we present the results of the steady-state calculations performed for the case when the external field is tuned into the resonance with the transition \( |1\rangle \leftrightarrow |3\rangle \) (\( \Delta_{31} = \omega_{31} - \omega_0 = 0 \)).

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\( \omega_0 = 0 \). Panel (b) shows the acting field magnitude \(|\Omega|\) as a function of the external field magnitude \(|\Omega_0|\) for the set of parameters typical for two-dimensional supercrystals built up of semiconductor quantum dots (SQD) [3]. As is seen from the plot, \(|\Omega|\) appears to be a multi-valued function of \(|\Omega_0|\), signaling multistability. The stability of different parts of the steady-state solution has been checked by analyzing the spectrum of Lyapunov exponents \( \Lambda_k \) \((k = 1, 2 \ldots 8)\). The maximal real part of \{\Lambda_k\}, \( \text{Max}\{\text{Re}[\Lambda]\} \), is plotted in panel (c).

**Fig. 1.** (a) – Excitation scheme of a QE (\( \Delta_{31} = 0 \)). (b) – Steady-state solution for \(|\Omega|\) as a function of \(|\Omega_0|\). Solid (dashed) parts of the curves indicate stable (unstable) regions of \(|\Omega|\). (c) – Real part of the major Lyapunov exponent \( \text{Max}\{\text{Re}[\Lambda]\} \) as a function of \(|\Omega|\). Parameters of calculations are: \( \Delta_{32} = 10 \), \( \gamma_R = 100 \), \( \Delta_L = 1000 \), \( \gamma_{32} = 0.01 \). All quantities is given in units of \( \gamma_{31} \).

**Fig. 2.** Left panel – the linear reflection coefficient \( R \) as a function of the detuning \( \Delta_{31} \). Right panel – the field dependence of \( R \) computed for a set of detunings \( \Delta_{31} \) shown in the plot. The value \( \Delta_{31} = 1700 \) is the threshold for bistability to occur. The rest of parameters are the same as in Fig. 1.

Fig. 2 shows the detuning and field dependence of the reflectance \( R = |\Omega_{\text{refl}}|/|\Omega_0|^2 \) (left and right panels, respectively), \( \Omega_{\text{refl}} = \gamma_R(p_{31} + p_{21}) \) is the Rabi amplitude of the reflected field. As follows from the left plot, the linear reflectance (for a week \(|\Omega_0|\), left panel) has a maximum at \( \Delta_{31} = 2000\gamma_{31} \). Moreover, at this point \( R \) is approaches unity, i.e. the monolayer almost totally reflects the input field. The right panel in Fig. 2 demonstrates arising three solutions for \( R \) at a given \(|\Omega_0|\), which means bistability of the reflectance.

Summarizing, we believe that a monolayer comprising V-type QEs may serve as a nanometric bistable mirror. These features might be of interest for nanophotonics. Supercrystals built up of SQDs with the degenerate valence band, e.g. CdSe, placed in magnetic field [4], can be considered as candidates for realization of such systems.

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**References**

1. R.F. Malikov, V.A. Malyshev, Opt Spectrosc. 122, 955 (2017)
2. V.A. Malyshev et al., J. Phys.: Conf. Ser. 1220, 012006 (2019)
3. M.P. Boneschanscher, W.H. Evers, J.J. Geuchies et al., Science 344, 1377 (2014)
4. Al.L. Efros, M. Rosen, M. Kuno et al., Phys. Rev. B. 54, 4843 (1996)