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Multistability and high reflectance of a mono-layer 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 mono-layer 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 Ω_0 and frequency ω_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 ω_{21} and ω_{31}, and spontaneous decay constants γ_{21} and γ_{31}. The doublet is described by the splitting Δ_{32} and the relaxation constant γ_{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 Ω acting on a given QE in the monolayer represents a sum of the external field Ω_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 ω_{21} and ω_{32} (relaxation constants γ_{21} and γ_{31}), depending on the population difference of corresponding transitions [1,2]. The effects are described by the constants Δ_L (shift) and γ_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 $|1\rangle\leftrightarrow|3\rangle$ ($\Delta_{31} = \omega_{31}$ –

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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 Λ_k ($k = 1,2\ldots8$). The maximal real part of $\{\Lambda_k\}$, Max{Re[Λ]}, is plotted in panel (c).

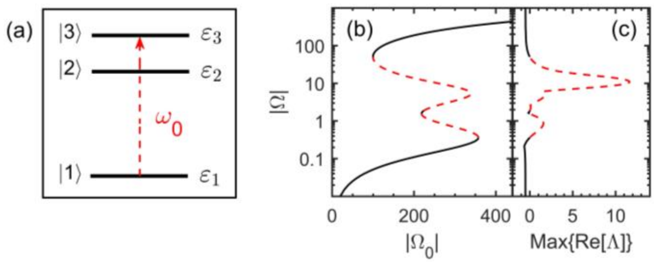

Fig. 1. (a) – Excitation scheme of a QE ($\Delta_{31} = 0$). (b) – Steady-state solution for $|\Omega|$ as function of $|\Omega_0|$. Solid (dashed) parts of the curves indicate stable (unstable) regions of $|\Omega|$. (c) – Real part of the major Lyapunov exponent Max{Re[Λ]} as a function of $|\Omega|$.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

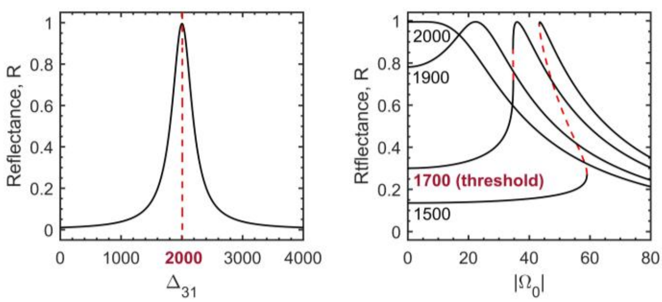

Fig. 2. Left panel – the linear reflection coefficient R as a function of the detuning Δ_{31}. Right panel – the field dependence of R computed for a set of detunings Δ_{31} shown in the plot. The value $\Delta_{31} = 1700$ is the threshold for bistability to occur. The rest of parameters are the same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

Fig. 2 shows the detuning and field dependence of the reflectance $R = |\Omega_{refl}/\Omega_0|^2$ (left and right panels, respectively), $\Omega_{refl} = \gamma_R(\rho_{31} + \rho_{21})$ 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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