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All-optical switching between quantum dot nanoarrays

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ABSTRACT

An all-optical switching device is proposed, based on a sandwich structure comprising two-dimensional square-lattice nanoarrays of donor and acceptor quantum dots. The system operates on Förster energy transfer between the dark states of the individual nanoparticles, normally precluded by selection rules. On application of an off-resonant laser beam, a nonlinear mechanism activates transfer between spatially correlated quantum dots across an optically passive spacer layer, signifying an active switching action with parallel processing capability. In this report, electrodynamic theory is employed to analyse the system and to evaluate its energy transfer fidelity. The results of model calculations are presented in graphical form.

1. Introduction

The construction of viable devices for all-optical switching is currently a goal of major commercial interest, whose long-awaited achievement is anticipated to bring about a revolution in telecommunications and computing [1–3]. One major advantage of all-optical switches over their conventional electronic counterparts is the circumvention of bottlenecks caused by opto-electronic conversion, facilitating ultrafast processing [4]. Another is a much higher level of energy efficiency in optical systems although, since photons do not directly interact with one another, matter is still required to act as the mediator. The devising of suitable material constructs therefore lies at the heart of current research and development efforts.

Quantum dots represent an attractive option as building blocks for photonic components, offering strong wavelength-selectable transitions and a high degree of photostability [5]. Amongst the wide-ranging investigations into such materials, a number of recent studies have focused on Förster resonance energy transfer (FRET) [6–10], nonlinear optical response [11,12] and all-optical switching

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[13,14]. In the present analysis, we examine an all-optical switching mechanism based on FRET between two quantum dots – i.e. the transfer of energy from an initially excited donor to an unexcited acceptor – with optical control of such transfer by a single input laser beam of sufficient intensity; experimentally this is much simpler than the previously considered dual-beam configurations [15–17]. Full details of the control mechanism for a single donor–acceptor pair has been presented elsewhere [18]. Our proposed all-optical switching device (which employs the control mechanism) is based on a sandwich structure that comprises a pair of parallel two-dimensional square-lattice nanoarrays – each composed of quantum dots – either side of an optically passive spacer layer. The spacing between individual dots in each array is chosen to minimize the electronic and optical coupling between them; as such, each is individually addressable.

An outline of our model is as follows: (i) any individual quantum dot within the donor nanoarray is indirectly excited to a 'dark' state (i.e. one whose direct dipolar population from the ground state is forbidden); (ii) the associated energy of excitation is transferred to a close-neighbour dot in the acceptor nanoarray, the donor and acceptor dots being chosen for a correlation in excited state positioning; (iii) the optically nonlinear activation of this energy transfer is only achieved through the presence of an intense non-resonant laser field — for example, the relevant quantum dot transitions may be two-photon allowed but single-photon forbidden. The ultimate aim is to optically control a 2D-distributed binary coding – where 1 and 0 denote excited and unexcited quantum dots, respectively – by influencing the excitation transfer from the dots in the donor (input) nanoarray to their partners in the acceptor (output) array. In other words, the binary pattern on the donor nanoarray is controllably transferred to the acceptor array, signifying an active switching with parallel processing capability. The output array is then 'read' by detection of the emission that follows the relaxation of the acceptor dots. The switching action is enabled since the throughput or absence of the laser input will cause activation or deactivation of the energy transfer process, respectively.

This paper will employ electrodynamic theory to analyse the described activation mechanism operating between an arbitrary excited quantum dot in the donor array and its unexcited close-neighbour dot in the acceptor array. Since pairwise coupling is also possible between the arbitrary excited dot and all the other dots, a quantitative measure of signal fidelity (the relative efficiency of targeted excitation transfer) is needed. An analytical expression for the latter is secured, and the results of model calculations are presented in graphical form.

2. Theory

To specifically determine the efficiency or probability, P, for occurrence of the activation (optically nonlinear) energy transfer mechanism, a time-dependent perturbation method is required. Results for the time derivative of P are secured from the Fermi Golden Rule [19], whose general application to energy transfer generates a converging sequence comprising even-order terms:

$$\overset{\bullet}{P} = \frac{2\pi \rho_f}{\hbar} \left| M_{fi}^{(2)} + M_{fi}^{(4)} + \cdots \right|^2, \tag{1}$$

where ρ_f is the density of electronic states at the excited electronic level of the acceptor. The quantum amplitude $M_{fi}^{(2)}$ relates to conventional energy transfer, which involves second-order coupling (two essentially simultaneous, coupled transitions — see Fig. 1). As our model assumes that the optically controlled energy transfer entails single-photon forbidden transitions, this mechanism need no longer be considered. Returning to Eq. (1), in which higher-order amplitudes diminish in magnitude, the amplitude $M_{fi}^{(4)}$ is now the leading term, corresponding to the activation mechanism. In detail, this fourth-order mechanism entails the simultaneous coupling of conventional energy transfer with pairwise absorption and stimulated re-emission of the input laser (Fig. 2). In the short-range region, $M_{fi}^{(4)}$ is generally obtained as [20]

$$M_{fi}^{(4)} = \left(\frac{I}{8\pi \varepsilon_0^2 c R^3} \right) e_i e_l \left(\delta_{jk} - 3\hat{R}_j \hat{R}_k \right) \left(\alpha_{ij}^{A} \alpha_{lk}^{B} + \alpha_{ij}^{B} \alpha_{lk}^{A} \right), \tag{2}$$