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Percolation of optical excitation mediated by near-field interactions

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HIGHLIGHTS

- Percolation of optical excitation transfer in randomly organized nanostructures.
- Two phases of percolation appear as a function of the light localization degree.
- Sublinear scaling emerges when the light localization is strong.
- Sublinear scaling also depends on the size of environments.

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ABSTRACT

Optical excitation transfer in nanostructured matter has been intensively studied in various material systems for versatile applications. Herein, we theoretically and numerically discuss the percolation of optical excitations in randomly organized nanostructures caused by optical near-field interactions governed by Yukawa potential in a two-dimensional stochastic model. The model results demonstrate the appearance of two phases of percolation of optical excitation as a function of the localization degree of near-field interaction. Moreover, it indicates sublinear scaling with percolation distances when the light localization is strong. Furthermore, such a character is maximized at a particular size

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of environments. The results provide fundamental insights into optical excitation transfer and will facilitate the design and analysis of nanoscale signal-transfer characteristics.

1. Introduction

Optical excitation transfer has been intensively studied various material systems [1–3] and utilized in versatile applications including nanobiosensors [4], solid-state lighting [5], signal conversion [6], optical switching [7], and intelligent functions [8]. The theory of optical excitation transfer has been explained by local optical near-field interactions, which describe optical excitation transfer involving conventionally dipole-forbidden transitions [9,10].

In experimental efforts, one critical concern is to regulate the sizes and positions of nanostructures so that optical near-field interactions are induced between them to obtain the desired functions. Thus, it is necessary to model nanophotonic devices and systems composed of multiple nanostructures arranged in varying configurations to characterize and design designated functions. In a previous study, we constructed a stochastic model to examine optical excitation transfer in multilayer quantum dot (QD) devices whereby the variation in QD size and temperature-dependent energy band broadening are concerned in a unified manner [11]. However, the spatial inhomogeneity was not considered and a better fundamental understanding needs to be developed; basic phenomena such as the percolation of optical excitation in random media have not yet been examined. Meanwhile, Nomura et al. demonstrated long-range optical excitation transfer in randomly distributed core–shell QDs [12]; such a system has been successfully utilized in intelligent devices for decision making [8]. Also, Kaneta et al. developed dual-probe scanning near-field optical microscopy (SNOM) and succeeded in visualizing detailed carrier diffusion/recombination processes in light-emitting semiconductors such as InGaN single quantum well [13,14]. The source and sink nodes in our model system introduced in the next section could correspond to the dual probes in such a near-field apparatus. However, the performance limitations, fundamental characteristics (e.g., robustness), and systematic analysis and design methodologies of these systems have not yet been clarified; hence, further insights into optical excitation transfer are required.

In this paper, we characterize the percolation behavior of optical excitation related to near-field interactions governed by Yukawa-type potential in a randomly organized nanoparticle system distributed on a two-dimensional system. The notion of percolation provided interesting insights into a broad range of scientific disciplines such as physics, materials science, and complex networks [15,16]. In this study, percolation refers to the optical excitation transfer from a source node to a sink node. By intentionally destructing internal material systems between these nodes, (i.e., deleting some elemental structures from the original system), we examine how the optical excitation transfer from the source to sink node is altered by considering the effects of optical near-field interactions. We demonstrate that two different types of percolation appear depending on the degree of localization of the optical near fields. Furthermore, we show that the distant-dependent percolation deviates from normal linear scaling when the light localization is strong as well as the fact that such deviation is maximized with a particular system size; i.e., the sublinear scaling also depends on the size of environments.

2. Model

We begin by reviewing some of the basic theoretical elements of optical excitation transfer mediated by near-field interactions [9,17]. We assume two spherical QDs with radii R_S and R_L (termed as QD_S and QD_L, respectively) located in close proximity (Fig. 1(a)). The energy eigenvalues of the states specified by quantum numbers (n, l) are given by

$$E_{nl} = E_g + E_{ex} + \frac{\hbar^2 \alpha_{nl}^2}{2MR^2} \quad (n = 1, 2, 3, \ldots), \tag{1}$$

where E_g is the band gap energy of the bulk semiconductor, E_{ex} is the exciton binding energy in the bulk system, and M is the effective mass of the exciton. α_{nl} are determined from the boundary conditions such as $\alpha_{n0} = n\pi$ and $\alpha_{11} = 4.49$. According to Eq. (1), the energy level of quantum number (1,0) in QD_S and that of quantum number (1,1) in QD_L are resonant with each other if $R_L/R_S = 4.49/\pi \approx 1.43$. Note that the optical excitation of the (1,1)-level in QD_L corresponds to an electric dipole-forbidden transition. An optical near field, denoted by U in Fig. 1(a), given by the Yukawa-type potential

$$U^{-1} = \frac{\exp(-\mu r)}{r} \tag{2}$$

allows this level to be populated due to the steep electric field in the vicinity of QD_S [9]. Here, r is the interdot distance and μ quantifies the degree of light localization given by

$$\mu = \frac{\pi}{a}\left(\frac{\sqrt{3}M}{m_e}\right) \tag{3}$$