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Control of the stability and soliton formation of dipole moments in a nonlinear plasmonic finite nanoparticle array

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Abstract

We perform numerical analysis of a finite nanoparticle array, in which the transversal dipolar polarizations are excited by a homogenous optical field. Considering the linearly long-range dipole–dipole interaction and the cubic dipole nonlinearity of particle, the characteristics of stability of a finite number nanoparticle array should be revised, compared with that of an infinite number nanoparticle array. A critical point in the low branch of the bistable curve is found, beyond which the low branch becomes unstable for a finite number of nanoparticles. The influence of the external field intensities and detuning frequencies on this critical point are investigated in detail. When the total number of particles approaches infinity, our results become similar to that of an infinity number particle system [32]. Notably, with appropriate external optical field, a dark dipole soliton is formed. Moreover, when the scaled detuning is set to an appropriate value, a double monopole dark soliton (DMDS) consisting of two particles is formed. The DMDS may have potential applications in the subwavelength highly precise detection because of its very small width.

Keywords: Bistability; Spatial solitons; Plasmonics

1. Introduction

Localized plasmon resonance [1] is the excitation of the conduction electrons of metallic nanostructures coupled to an electromagnetic field. This effect leads to field amplification both inside and outside (in the near-field zone) the metal nanoparticles. These resonances, which may be used in optical sensing, generally depend on the type of metal, the shape of nanoparticles and the dielectric environment within the electromagnetic near field [2–7]. Nanoparticles are also used to constitute a subwavelength waveguide. Metallic nanoparticles arranged into arrays can spatially confine and manipulate optical energy in a distance much smaller than the wavelength [8–12]. In addition, the strong geometric confinement of the optical field in these nanoparticle arrays can boost the efficiency of nonlinear optical effects such as the frequency conversion, modulation of optical signals, and the formation of solitons [13].

Nonlinear plasmonics [13] which involves the excitation of nanostructures by an external field, is an emerging research field. In practice, using the field

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penetration inside the nanostructures to generate the resonance plasmonic, many optical nonlinear effects can be boosted [14]. These effects include self-phase modulation in structured nanoparticles arrays [15], second and third harmonic generation in nanostructured metal films and nanoantennas [16–22], subwavelength solitons in different nanostructures including multilayers [23–25], nanowires arrays [26–28], Kerr nonlinear coupled-cavity array [29], and two-dimensional lattices [30]. Recently, considering the linear dipole–dipole interaction, cubic dipole nonlinearity, and other related environment parameters, Noskov et al. analyzed the modulation instability and bistability of optical-induced dipoles and discussed several novel nonlinear effects, which include domain walls as well as the bright and dark oscillons and solitons in a metallic spherical nanoparticle array [31–33]. They performed the stability analysis using an infinite number particle system. We continue the previous works, considering the finite system, and achieve some interesting results, two of which are: first, demonstrating in detail the difference of instability areas between the infinite and finite systems consisted of nanoparticle arrays. From a practical point of view, the system of finite nanoparticle arrays should be considered and the edge effects must be addressed, both of which have been considered in this paper; second, illustrating the width variation of dipole solitons with different initial conditions. Particularly, with suitable settings, we achieve dipole solitons with extremely narrow width.

This paper is organized as follow. The stability analysis for this system is discussed in Section 2. Based on the analysis in Section 2, we propose a scheme to generate dark dipole solitons and control the width of such solitons in Section 3. We demonstrate that the width of a dark soliton can be controlled by an external field and different detuning frequencies. Moreover, when the scaled detuning is set to $-0.11 \leq \Omega \leq -0.08$, two-particle double monopole dark soliton (DMDS), with an approximate width of 30 nm, is achieved. The paper is concluded in Section 4.

2. Model and stability analysis

We consider the system consisted of identical spherical silver nanoparticles which are arrayed linearly equidistant with each other and embedded into an SiO_2 host (seen from Fig. 1). Specific parameters of the system are shown in the Appendix.

The nonlinear dynamic of dipoles induced by the field in the nanoparticle arrays can be described by the following equations [31–33]:

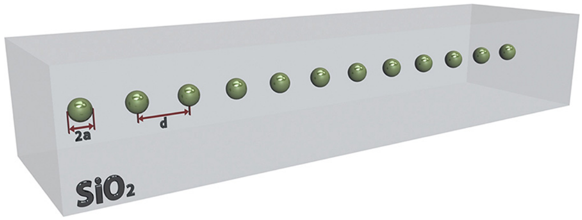

Fig. 1. Schematic sketch of an array of silver spherical nanoparticles embedded into an SiO_2 host, radius of sphere is a and the center-to-center distance is d.

$$-i\frac{dP_n^{\perp}}{d\tau}+(-i\gamma+\Omega+|P_n|^2)P_n^{\perp}+\sum_{m\neq n}G_{n,m}^{\perp}P_m^{\perp}=E_n^{\perp}, \tag{1}$$

$$-i\frac{dP_n^{\parallel}}{d\tau}+(-i\gamma+\Omega+|P_n|^2)P_n^{\parallel}+\sum_{m\neq n}G_{n,m}^{\parallel}P_m^{\parallel}=E_n^{\parallel}. \tag{2}$$

In Eqs. (1) and (2), $P_n^{\perp,\parallel}=p_n^{\perp,\parallel}\sqrt{\chi^{(3)}}/(\sqrt{2(\varepsilon_\infty+2\varepsilon_h)}\varepsilon_h a^3)$ are the dimensionless slow-varying amplitudes of the vertical and parallel dipoles of the nth particle, respectively. The indices '$\perp$' and '$\parallel$' represent the vertical and parallel directions with respect to the array axis, respectively. Thus the total intensity of the dipole for the nth particle is given as $|P_n|^2=|P_n^{\perp}|^2+|P_n^{\parallel}|^2$. $\gamma=\nu/(2\omega_0)+(k_0a)^3\varepsilon_h/(\varepsilon_\infty+2\varepsilon_h)$, with $k_0=\omega_0/c\sqrt{\varepsilon_h}$ is the scaled damping. $\Omega=(\omega-\omega_0)/\omega_0$ is the detuning frequency of the dipoles. When incident wavelength is about 400 nm, $\Omega=0$ for silver particle. $\tau=\omega_0 t$ is the scaled elapse time. $E_n^{\perp,\parallel}=-3\varepsilon_h\sqrt{\chi^{(3)}}E_n^{\mathrm{ex},\perp,\parallel}/\sqrt{8(\varepsilon_\infty+2\varepsilon_h)^3}$ are also the slow varying amplitudes of the external optical fields in the respective directions. $G_{n,m}^{\perp,\parallel}$ is the linearly coupled parameter between the nth and mth particles in the corresponding directions and is induced by the long-range dipole–dipole interactions. $G_{n,m}^{\perp,\parallel}$ can be expressed:

$$G_{n,m}^{\perp}=\frac{\eta}{2}\left[(k_0d)^2-\frac{ik_0d}{|n-m|}-\frac{1}{|n-m|^2}\right]\frac{e^{-ik_0d|n-m|}}{|n-m|}, \tag{3}$$