Oscillons, solitons, and domain walls in arrays of nonlinear plasmonic nanoparticles

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Abstract

We study analytically and numerically modulational instability in arrays of nonlinear plasmonic nanoparticles, and demonstrate that it can lead to the formation of long-lived standing and moving nonlinear localized modes of three different types – domain walls connecting the states with different polarizations as well as solitons and oscillons with stationary and oscillating profiles. We analyze properties of these modes and show their transformation from one type to another.

1. Introduction

Nonlinearity-induced instabilities are observed in many different branches of physics, and they provide probably the most dramatic manifestation of strongly nonlinear effects that can occur in nature. Modulational instability (MI) in optics manifests itself in a decay of broad optical beams into optical filaments (or pulse trains) [1, 2], and such effects are well documented in both theory and experiment. It is expected that the study of subwavelength nonlinear systems such as metallic nanowires or nanoparticle arrays may bring many new features to the physics of MI and the scenarios of its development; however, such effects have attracted researcher's attention only recently.

Over the past decade, surface plasmons were suggested as the mean to overcome the diffraction limit in optical systems. In particular, by using plasmons excited in a chain of resonantly coupled metallic nanoparticles, one can spatially confine and manipulate optical energy over distances much smaller than the wavelength. In addition, strong geometric confinement can boost efficiency of nonlinear optical effects, including the existence of subwavelength solitons [3, 4], and generation of THz radiation from nonlinear metallic nanodimers [5].

In this work, we study MI in subwavelength nonlinear systems for an array of optically driven metallic nanoparticles with a nonlinear response. We demonstrate the existence of novel types of nonlinear effects in such systems, including formation of domain walls (or switching waves) connecting the states with different stationary or dynamical polarizations as well as generation of long-lived standing and moving nonlinear localized modes in the forms of oscillons [6] and solitons. We reveal that a wide variety of scenarios of MI development allows mode transformation from one type to another, changing movement direction and a velocity of drifting oscillons and solitons, and formation of stable domain walls connecting not only different stationary states but also the states with different types of nonlinear dynamics (e.g., chaotic-like and regular).

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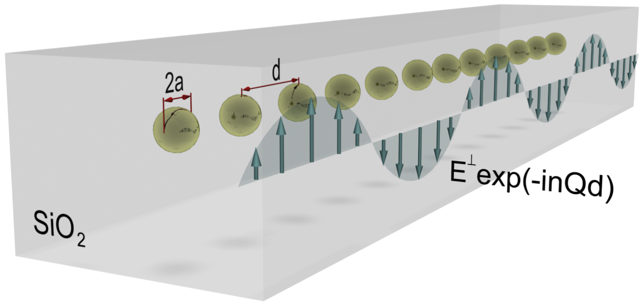

Fig. 1: Schematic sketch demonstrating a geometry of the studied problem. Arrows indicate modulated external field. Transversal (with respect to the chain axis) field polarization is shown, but the case of the longitudinal polarization has also been considered.

2. Model and results

Figure 1 shows the geometry of our problem: a chain of identical spherical silver nanoparticles embedded into a fused silica host medium with permittivity ε_h and driven by an arbitrary modulated optical field with the modulation wavenumber Q and the frequency close to the frequency of the surface plasmon resonance of an individual particle ω_0. We assume that the particle radius and distance between the particles are $a = 10$ nm and $d = 30$ nm, respectively. The ratio a/d satisfies the condition $a/d \leq 1/3$, so that we can employ the point dipole approximation. In the optical spectral range, a linear part of silver dielectric constant can be written in a generalized Drude form $\varepsilon^{\mathrm{L}}_{\mathrm{Ag}} = \varepsilon_\infty - \omega_p^2/[\omega(\omega - i\nu)]$, where $\varepsilon_\infty = 4.96$, $\hbar\omega_p = 9.54$ eV, $\hbar\nu = 0.055$ eV [8]; whereas dispersion of SiO_2 is neglected since $\varepsilon_h \simeq 2.15$ for wavelengths 350-450 nm. The nonlinear dielectric constant of silver is $\varepsilon^{\mathrm{NL}}_{\mathrm{Ag}} = \varepsilon^{\mathrm{L}}_{\mathrm{Ag}} + \chi^{(3)}|\mathbf{E}_n^{(\mathrm{in})}|^2$, where $\mathbf{E}_n^{(\mathrm{in})}$ is the local field inside nth particle. We keep only cubic susceptibility due to spherical symmetry of particles. According to the model suggested in Ref. [9] and confirmed in experiment, 10 nm radii Ag spheres possess a remarkably high and purely real cubic susceptibility $\chi^{(3)} \simeq 3 \times 10^{-9}$ esu, in comparison to which the cubic nonlinearity of SiO_2 is weak ($\sim 10^{-15}$ esu).

We study nonlinear dynamics of the chain by employing the slowly varying envelope approximation. This approach is based on the assumption that in the system there exist small and large time scales, which in our case is fulfilled automatically since each particle acts as a resonantly excited oscillator with slow (in comparison with the light period) inertial response. More specifically, we use the system of coupled equations for slowly varying amplitudes of the particle dipole moments obtained in Ref. [6, 7] which takes into account all particle interactions through the dipole fields, and it can be employed for both finite and infinite chains. Having found the stationary solution of this system, we analyze its linear stability with respect to weak spatiotemporal modulations taken in the form of chain eigenmodes with the modulation wavenumber K and show that the stability depends on the external field intensity, frequency, modulation wavenumber as well as K.

Once the parameters of the external field satisfy the criteria of MI, the initial stationary state becomes unstable, and the subsequent evolution of the system is defined by a spectrum of eigenmodes excited due to MI. In particular, the development of MI can result in (i) stationary periodic modulation of the particle polarizations, (ii) periodic temporal beating, (iii) chaotic-like behavior of particle polarizations, (iv) appearance of domain walls connecting the particles in different stationary or dynamical states, and (v) formation of long-lived nonlinear localized states in the form of plasmon-solitons and/or plasmon-oscillons with stationary and oscillating profiles.

Figure 2 shows two examples of the latter case: (a) excitation of a train of bright oscillons moving from the right edge to the left edge of the chain, where they radiate; (b) generation of a slowly drifting oscillon

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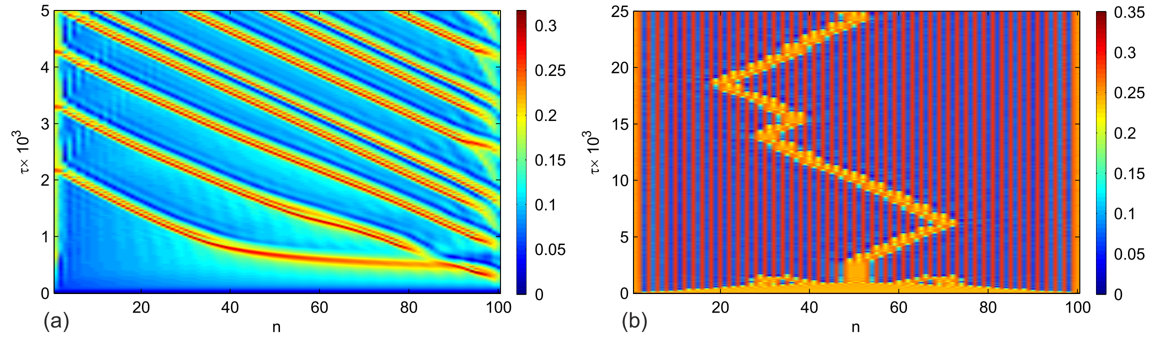

Fig. 2: Dynamics of the dimensionless particle dipole moments (modulus is plotted) obtained by numerical simulations for a finite chain (with 100 nanoparticles) excited (a) longitudinally with $Qd = 0.7$, $\Omega = -0.03$, $|E^{\parallel}|^2 = 10^{-5}$, and (b) transversally with $Qd = \pi$, $\Omega = -0.047$ and $|E^{\perp}|^2 = 7 \times 10^{-5}$. Here $\tau = \omega_0 t$ is the dimensionless time, $\Omega = (\omega - \omega_0)/\omega_0$ is the frequency shift from the resonant value, $E^{\parallel,\perp}$ are the dimensionless slow varying amplitudes of the external field [6, 7].

with varying direction of motion. In both the cases we observe the transformation of solitons to oscillons. Reversed oscillon-to-soliton transformations are also possible. In addition, moving oscillons/solitons can be pinned by the edges of the chain, turning into surface states.

3. Conclusion

We have studied theoretically modulational instability in arrays of nonlinear metallic nanoparticles, and analyzed numerically the development of the instability beyond the linear regime. We have observed that modulational instability can lead to the formation of long-lived standing and moving domain walls, solitons, and oscillons. We have analyzed the properties of these localized modes and shown mode transformation from one type to another. The experimental observation of the predicted modulational instability can provide a prominent approach to achieve subwavelength confinement of the optical fields guided by plasmonic nanostructures.

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