Spaser chains

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Abstract

We show that depending on the values of the coupling constants, two different scenarios for the stationary behavior of a chain of interacting spasers may be realized: (1) all the spasers are synchronized and oscillate with a unique phase and (2) a nonlinear autowave travels along the chain. In the latter scenario, the traveling wave is *harmonic*, unlike excitations in other known nonlinear systems. Due to the nonlinear nature of the system, any initial distribution of spaser states evolves into one of these steady states.

1. Introduction

In the last decade, quantum nanoplasmonics has experienced explosive growth due to numerous revolutionary applications in optics and optoelectronics [1]. A combination of a nanoscale active medium with the population inversion results in the emergence of a nanoplasmonic counterpart of the laser – surface plasmon amplification by stimulated emission of radiation (spaser) first proposed by Bergman and Stockman [2] and realized experimentally by Noginov et al. [3]. A single spaser consists of a metal nanoparticle (NP) coupled with a quantum dot (QD) which population inversion caused by an external source. Above the threshold inversion, the spaser generates a coherent near-field, localized at the metal NP.

If spasers are used as a gain medium for the loss compensation, one must understand the functioning of a system of interacting spasers distributed regularly or randomly in a dielectric matrix. In the present communication, we theoretically study the collective interaction of self-oscillationing spasers above the spasing threshold. We consider the simplest example of a spasers array – a regular chain of spasers. In this case, the collective near-field interaction between spasers can significantly change the threshold of the generation and even lead to new phenomena and instabilities in these structures.

2. Collective excitations of spaser chains

We show that depending on the strength of the interaction between the QD and the NP of the nearest spasers, either a synchronized oscillation of all the spasers in the chain or a harmonic autowave travelling along the chain may realize. The pumped QD may either excite its own spaser so that all spasers are synchronized or cooperating with the other QDs, the pumped QD may excite a plasmonic wave traveling along the chain. This is the wave of the NP polarization which dispersion equation $\omega(k)$ is similar to the one predicted in Refs. [4] -[7] for linear systems such as a chain of plasmonic NPs. This dispersion equation has the form

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$$\omega(k) = \frac{\omega_{SP}\tau_a + \omega_{TLS}\tau_\sigma}{\tau_a + \tau_\sigma} + \Omega_{NP-NP}^{eff} \cos kb \quad (1)$$

where $\Omega_{eff} = 2\Omega_{NP-NP}\tau_a / (\tau_a + \tau_\sigma)$, Ω_{NP-NP} is the coupling constant between neighboring NP, ω_{SP}, τ_a, ω_{TLS}, and τ_σ are frequencies and relaxation times of the surface plasmon and the two-level QD, respectively, b is the distance between neighboring spasers. Unlike the general case of a wave propagating in a nonlinear lattice [4], the nonlinear character of the spasers' response to an external field results neither in soliton nor in kink solutions. Rather, this response is a perfectly harmonic wave. However, unlike harmonic waves in linear systems, in a chain of spasers, this wave has a fixed value of the wavenumber, which depends on the coupling constant between the QD and the NP of neighboring spasers, Ω_{NP-TLS}. For positive values of the coupling constant, Ω_R, of the QD and the NP inside the spaser, we have

$$kb = \begin{cases} \pi, & \Omega_{NP-TLS} < -\Omega_{NP-TLS}^* \\ \cos^{-1}\left(\dfrac{2\Omega_{NP-TLS}}{\left(\tau_\sigma \Omega_{NP-NP}^{eff}\right)^2 \Omega_R} \right), & -\Omega_{NP-TLS}^* \le \Omega_{NP-TLS} \le \Omega_{NP-TLS}^* \\ 0, & \Omega_{NP-TLS} > \Omega_{NP-TLS}^* . \end{cases} \quad (2)$$

and for $\Omega_R < 0$

$$kb = \begin{cases} 0, & \Omega_{NP-TLS} < -\Omega_{NP-TLS}^* \\ \pi - \cos^{-1}\left(\dfrac{2\Omega_{NP-TLS}}{\left(\tau_\sigma \Omega_{NP-NP}^{eff}\right)^2 \Omega_R} \right), & -\Omega_{NP-TLS}^* \le \Omega_{NP-TLS} \le \Omega_{NP-TLS}^* \\ \pi, & \Omega_{NP-TLS} > \Omega_{NP-TLS}^* . \end{cases} \quad (3)$$

Here Ω_{NP-TLS}^* is the threshold value of coupling constant between QD and NP of neighboring spasers

$$\Omega_{NP-TLS}^* = 0.5\left(\tau_\sigma \Omega_{NP-NP}^{eff}\right)^2 \Omega_R \quad (4)$$

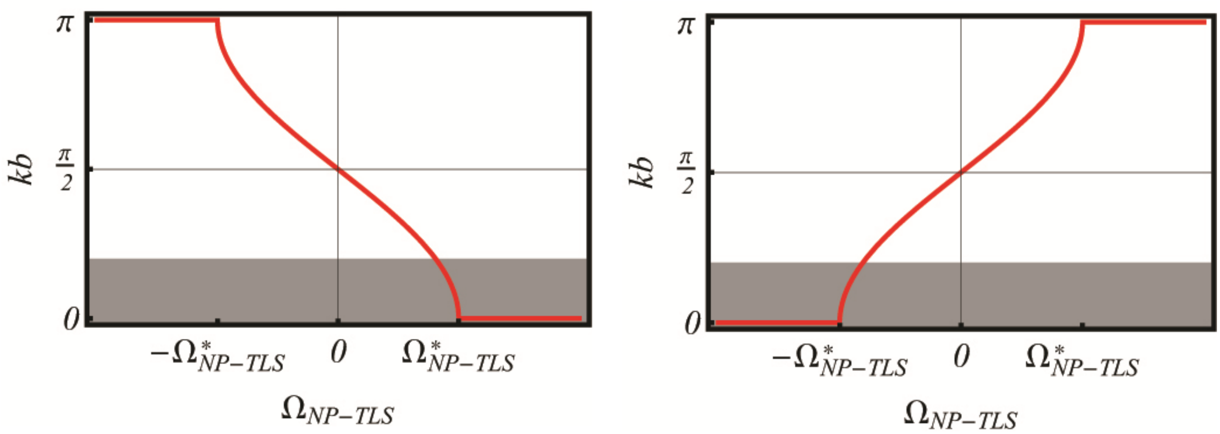

Fig. 1. The dependencies of the wave number of stable solution of Eqs. (2) and (3) for $\Omega_R > 0$ and $\Omega_R < 0$ respectively. The shaded areas correspond to leaky wave solutions (see the comment at the end of conclusion).

From Fig.1, one can see that depending on the value of the coupling constant, Ω_{NP-TLS}, two different scenarios for the stationary behavior of a chain of interacting spasers may be realized: (1) all the spasers are synchronized and oscillate with in phase and (2) a nonlinear autowave travels along the chain. In the latter scenario, the traveling wave is *harmonic* unlike excitations in other known nonlinear systems [8]. The amplitude of this wave and its wave number are strictly determined by pumping and the coupling constants. Due to the nonlinear nature of the system, any initial distribution of spasers' polarization evolves into one of these steady states.

3. Conclusion

In this paper, we have studied excitations in a chain of interacting spasers. We have shown that, depending on the strength of the interaction between a QD and the nearest NP, either a synchronized oscillation of all the spasers or a harmonic autowave travelling along the chain may arise. Thus, the pumped QD may either excite its own spasers so that all spasers are synchronized or cooperating with the other QDs, the pumped QD may excite a plasmonic wave traveling along the chain. This is the wave of NP polarization whose dispersion is similar to that predicted in Refs. [4] - [7] for linear systems. Unlike the general case of a wave propagating in a nonlinear lattice [8], the nonlinear character of the spasers' response to an external field results neither in soliton nor in kink solutions. Rather, the response is a perfectly harmonic wave. However, unlike harmonic waves in linear systems, in a chain of spasers, (*i*) the wave has a fixed value of the wavenumber, which is determined by the minimum value of the pumping threshold and the values of the coupling constants, (*ii*) its amplitude also has a fixed value, which is determined by the pumping strength, and (*iii*) its propagation direction is determined by the initial conditions.

The results obtained are valid for synchronized waves with wavenumbers k greater than an optical wavenumber in the surrounding space k_0. If $k < k_0$, the waves become leaky, radiative emission becomes substantial and the lasing would be initiated in the spaser [9].

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