Superradiance in 2D spaser array

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Abstract

We demonstrate that a 2D array of spasers may be synchronized. Since in the sole spaser the joule losses exceed radiation ones it is the near fields of surface plasmons that are amplified. In the array of synchronized spasers due to superradiance the radiation of photons prevails over the joule losses and spasers start working as nanolasers. Since the synchronization is due to near field interaction the system size may be greater than the wavelength, opposite to the case of usual supperradiance. Thus, the aperture of the system may be chosen greater than wavelength that results in narrowing of the radiation pattern and in cubic dependence of the intensity on the number of spasers.

1. Introduction

Recently, a new branch of quantum optics – quantum nanoplasmonics – has arisen [1,2]. Advantageous plasmon properties such as small wavelength and a high energy concentration open new perspectives for constructing nano-devices such as waveguides, cavities, and antennas. In this regard, studies of plasmons propagating along 1D objects such as wires [3], wedges [4,5] and channels [6,7] are of great interest.

Losses in metals are the main obstacle to practical applications of plasmonics. It has been suggested that this problem can be overcome by compensating loss in a gain medium. This relates nanoplasmonics to quantum optics. In particular, a generator of plasmons propagating along a flat surface has been suggested in Ref. 8. In this system, periodic surface corrugations produce Bragg mirrors of the resonator cavity. The first quantum nanoplasmonic device which was referred to as spaser (Surface Plasmon Amplification by Stimulated Emission of Radiation) was proposed in Ref. 1. The spaser consists of a quantum dot (QD) located near a metal nanoparticle (NP). The plasmonic oscillations in the NP play the role of photons in a laser and the cavity effect is provided by the plasmon localization in the vicinity of the NP. Thus, a pumped QD nonradiatively transfers its excitation to surface plasmons localized at the NP. As a result, one observes an increase of intensity of the surface plasmon field. Thus, the spaser does not radiate an energy beam but generates a near field. The spaser has recently been realized [9].

In the current paper we suggest a new type of intense coherent light source based on superradiance of 2D array of interacting spasers. The reason for the superradiance is the synchronization of spasers, at which the plasmon ascillations become in-phase. In that case the amplitudes of the dipole moment oscillations $\mathbf{d}$ are summed to produce the dipole moment of $N\mathbf{d}$ for the whole system of N spasers. The intensity is then proportional to N^2, which is characteristic of the Dicke superradiance. The ab-

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sorption in the nanoparticles grows linearly with N, so that the relation between the absorption and radiation shifts towards the latter. Thus, the spaser property to radiate inside itself can be avoided by merging the spasers into array.

Another useful property of the synchronization is the radiation directivity. Indeed, the diffraction divergence of the beam θ is inversely proportional to the system size $\sqrt{N}$ (the distance between the spasers is assumed fixed). In that case, the radiation occurs in the angle $\delta\Omega \sim \theta^2$, which is inversely proportional to N. Than the angular radiation intensity is amplified both due to superradiance and due to directivity, i.e., $\delta I / \delta\Omega \sim N^3$.

2. Synchronization and superradiance

2D spaser array may be realized as a perforated metallic film placed at a subwavelength distance from a p-n junction. The voids in the film, manifesting plasmonic modes with in-plane dipole moments, play the role of nanoparticles. The p-n junction is modelled as a descrete set of two-level systems (quantum dots), Fig. 1.

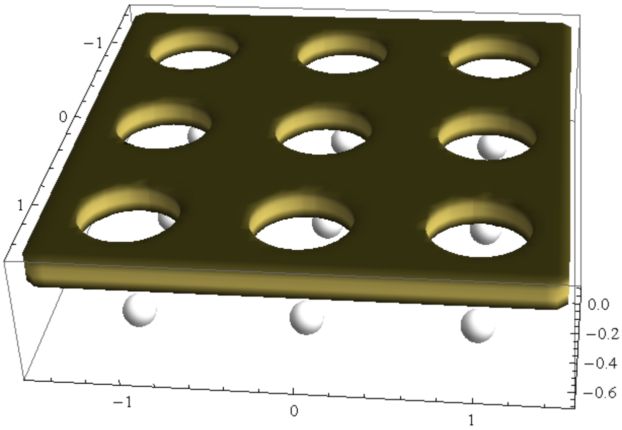

Fig. 1: System geometry.

Each spaser in the array is described by usual spaser dynamic equation system [10], but the interaction of each nanoparticle with neighbouring ones and with the neighbouring quantum dots is included. The resulting stationary solution is found to display synchronization, which is seen from the phase distribution (Fig. 2). One observes some boundary perturbations, which do not grow when the system size is increased. The anisotropy is related to the direction of the dipole moments.

The synchronized system radiates energy in the direction perpendicular to the array plane. The growth of the system size leads to the radiation directivity, so that the diffraction pattern extends in the direction perpendicular to the plane.

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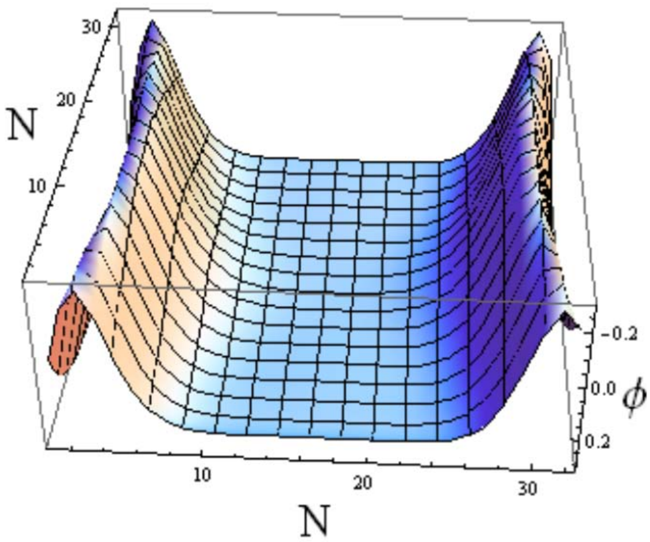

Fig. 2: Phase distribution in the synchronized spaser array.

4. Conclusion

Thus, the spaser array can be synchronized by interaction of a quantum dot with neighboring plasmonic nanoparticles. This causes two effects: superradiation, shifting the spasers to radiation instead of absorption, and radiation directivity. The result is the cubic dependence of the angular radiation density on the array size.

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