Extended dynamics and lasing of nanoemitters enhanced by dispersive carbon nanotubes

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Abstract

We investigate the extended dynamics and laser emission of random nanoemitters attached in a three-dimensional (3D) array of dispersed carbon nanotubes (CNTs) enhanced by plasmonic-polariton excitations. We found that in such a composite system, the onset time of laser generation (instability) in the nanoemitters significantly depends on the plasmonic frequency of the nanotubes. In the case of CNTs with a high plasmonic frequency, surface plasmon-polaritons are excited macroscopically, which leads to strong cross-coupling of emitter radiation to re-excited plasmon-polariton fields. The latter leads to a significant decrease in the onset time of laser instability. We found a resonant change in the field structure in the system associated with plasmon-polariton generation when the field of emitters in 3D clusters is strongly coupled to the CNT field. The corresponding resonance is detected in the form of a strong and narrow peak of the inverse participation ratio. The position of this resonance weakly depends on the number of attached emitters.

1 Model and basic equations

We consider periodic array of single-walled parallel carbon nanotubes (CNT) and a number of radiating nanoemitters attached randomly between of CNTs. To investigate the dynamics of this complex nonlinear 3D system we use the Maxwell equations for electrical **E**(r,t) and magnetic **H**(r,t) fields, polarization **P**(t), and four-level laser populations $N_{0,1,2,3}(t)$ of nanoemitters (quantum dots) [1-4]. However such nonlinear 3D system cannot be solved analytically, therefore in this study we use the numerical FDTD simulations allowing obtaining the exact solutions for photonic radiating field.

1.1 Lasing in the system with carbon nanotubes

We consider single-walled CNTs and a number **N** of radiating emitters (quantum dots (QD)) are randomly placed between the nanotubes. We study the radiating in such a compound system (emitters with surrounding CNT) at different values of the plasma frequency ω_p when the surface plasmon-polaritons (SPP) in CNT can be generated. Fig.1 shows the integral output flux of field energy that can be written as $I(t)=\oint_S(\mathbf{K}\cdot\mathbf{n})dS$ where $\mathbf{K}$ is the Poynting vector

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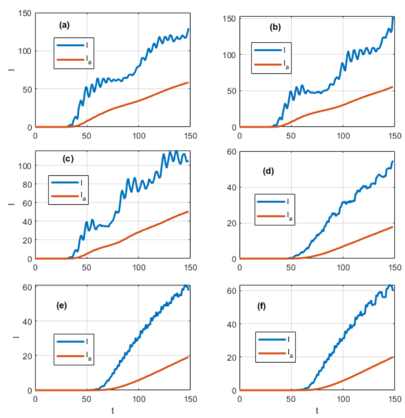

Figure 1. Integral intensity I(t) of field radiating by nanoemitters for different plasma frequencies ω_p.

From Fig. 1 one can see that the flux of the field energy $I(t)$ from the CNT array significantly depends on ω_p of surrounding CNT. We can conclude that the frequency $\omega_c=\omega_p=1.0\times10^8\,\mathrm{sec}^{-1}$ (when the plasmon-polaritons are generated) indicates the characteristic frequency that separates two regimes in considered compound system.

Fig.1 shows that the field dynamics and lasing of N random nanoemitters considerably depends on ω_p of surrounding CNT.

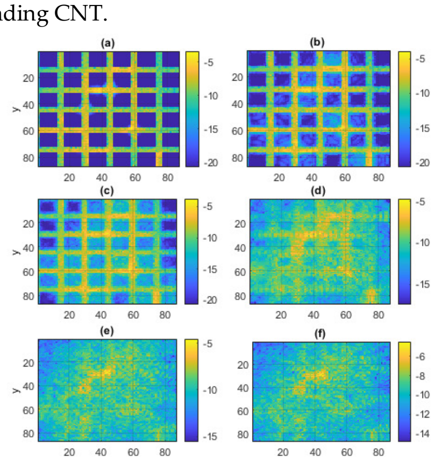

Figure 2. Spatial field distribution in the central plane at different ω_p of surrounding CNT.

Fig.2 shows that at large ω_p the field is concentrated near the boundaries and gaps between the CNTs and practically does not penetrate inside the nanotubes. At smaller values of $\omega_p <= 1.0\times10^8 \sec^{-1}$ (see panels (d), (e), and (f)) the field **E** is near homogeneous, where only the point-like radiating emitters are visible. In such a ω_p frequency range the SPPs can not propagate. Because of the significantly inhomogeneous shape of the field distribution (Fig.2), it is important to quantify the characteristics of the spatial features of plasmon-polariton field to decide how much the photonic field state **E** is ordered. To do that we calculate the Inverse Participation Ratio (IPR) defined as the normalized integral over the square of the field energy that reads

$$IPR = \frac{L^3 \int |\mathbf{E}|^4 d^3r}{\left(\int |\mathbf{E}|^2 d^3r\right)^2} = \left(\frac{L}{\Lambda}\right)^3.$$

We numerically found that IPR has very sharp peak at $\omega_c = \omega_p = 1.0\times10^8 \sec^{-1}$ (shown in Fig.3) that thus can be declared as critical frequency (resonance) of SPP generation. The position of ω_c is practically independent on the number of emitters N.

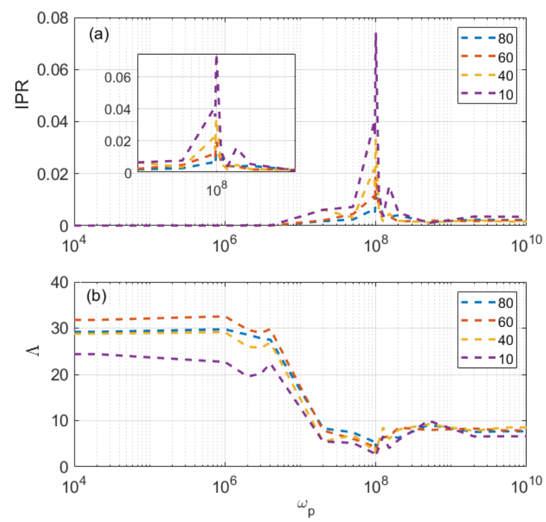

Figure 3. *(a) The Inverse Participation Ratio (**IPR**) of the radiating field in CNT lattice as function of the plasma frequency ω_p for different number of emitters. (b) The localization length of the field **Λ** in the CNT lattice as function of plasma frequency ω_p. We observe that IPR has very sharp peak at $\omega_p = \omega_c = 10^8 sec^{-1}$ that can be mention as a critical frequency and corresponds to surface PP generation. The position of ω_c is practically independent on the number of emitters N.*

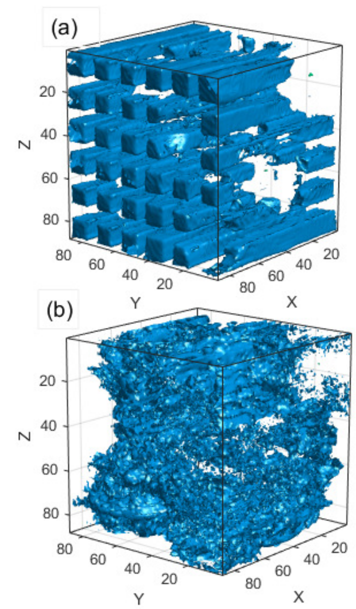

Figure *4. The spatial 3D structure of plasmon-polariton field in CNT array at different plasma frequency (a) $\omega_p = \omega_c = 10^8 sec^{-1}$ that corresponds to the incipient ordering state of field, and (b) disordered field state below the critical $\omega_p = 10^7 sec^{-1} < \omega_c$.*

2 Acknowledgement

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3 References

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