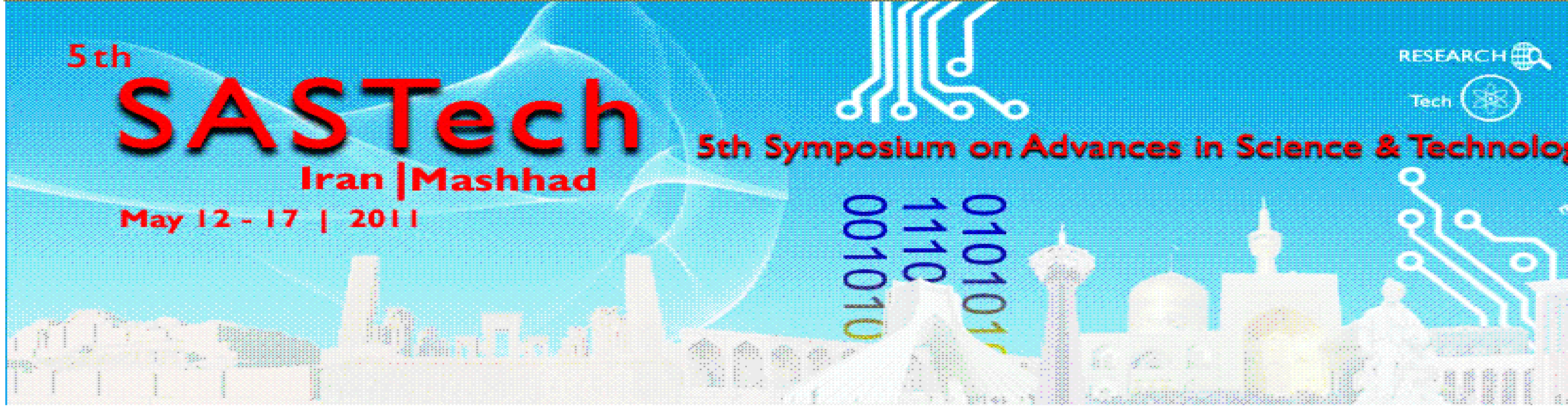

Dipole nanolaser

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Abstract

In this paper, we study the emitted light of the dipole nanolaser proposed by Protsenko et al. [Phys. Rev. A 71, 063812 (2005)] with attention directed to noise source by using of quantum Langevin formulations. with the steady state solutions, threshold condition for the lasing operation, spectrum of the intensity of the light, spectral line width and the number of the photon emitted are considered. Photon this light has a very wide frequency range, but for specific materials, line width can be reduced than to line width of the NP. Flux emitted by the DNL compare with that of an ordinary laser.

Key words: Nanolaser, Nanoparticle, Quantum dot, Surface Plasmon.

1. Introduction

Recent technological advances allow entire optical systems to be lithographically implanted on small silicon chips. These systems include tiny semiconductor lasers that function as light sources for digital optical signals. Future advances will rely on even smaller components. At the theoretical limit of this process, the smallest lasers will have an active medium consisting of a single atom.Several suggestions for how this can be accomplished have already been published, such as nano-lasers based on photonic crystals[4], Spaser[2],quantum dots[3] and nano wires lasers [6].

A dipole nanolaser(DNL) is consisting of a nanoparticle(NP) and a two-level system(TLS) with population inversion. If the threshold conditions are fulfilled, the dipole interaction between the two-level system and the nanoparticle leads to coherent oscillations in the polarization of the particles, even in the absence of an external electromagnetic field[9].

The quantum dot functioning as the active medium. It is optically coupled to metal nanoparticles that form a resonant cavity. Laser light is generated from the near-field optical signal.

Equations for dipole lasing are the same as equations for ordinary laser, where the dipole momentum of nano-particle stands for the electromagnetic field cavity mode[8].
It does not need an optical cavity, and has a very small volum, witch can be important for applications in microelectronics.
The minimum volume of conventional miniature lasers, is restricted by the volume of a cavity mode, which is, typically, greater than the cube of the lasing wavelength. Because the DNL uses near-field interactions, the DNL does not need an optical cavity and may have a volume$\ll\lambda^3$, which could be of benefit for a wide range of applications, including microelectronics.
The spaser approach has some features in common with the DNL. In particular, the spaser does not need an optical cavity. The spaser, however, operates in a regime that generates near-field modes, while the DNL generates polarization. The DNL approach could be referred to as "polarization amplification by stimulated emission of radiation" (PASER).
The quantum properties of the emitted light from DNL, will be studied with langevin formulations, with attention directed to noise sources. In Sec. II the equations for dipole laser are derived and threshold conditions are found. In Sec. III, With solve of steady state solution, find the threshold conditions for lasing operation. in Sec. IV, the spectrum of intensity of the light, the number of photon emitted and spectral line width is considered. Results are summarized in Conclusion and show that There are two extreme types of DNL, one corresponding to polariton lifetimes very long compared to the quantum dot lifetime and the other to very short polariton lifetimes.

2. Equations of Motion

Suppose that a TLS of size r_2 is placed at a distance r from a nanoparticle of size r_0 in a solid dielectric or semiconductor. An incoherent pump provides a population inversion in the TLS. The pump may be, for example, a broadband optical pump to a higher level of the TLS, as in a three-level laser pump scheme, or may be provided by carrier injection from the bands of a semiconductor material surrounding an embedded quantum dot[9].
we will carry out our analysis of the quantum optical properties of DNL using the Langevin formalism to model stochastic processes such as spontaneous emission and thermal fluctuation. The Hamiltonian is given by

$$H = \hbar\omega_0 a_H^\dagger a_H + \frac{\hbar\omega_0}{2}\sigma_{H,z} + H_{res,0} + V + H_{irrev} \qquad (1)$$

a_H , σ_H denote Heisenberg operators for the NP and TLS respectively where we are using σ to denote the pauli matrices. V is the dipole-dipole interaction between TLS and NP[9]; $H_{res,0}$ is the self-energy of the reservoirs to which the system is coupled; and H_{irrev} describes coupling between these reservoirs and the DNL.

$$\hat{V} = -\vec{E}.\widehat{\mu_2}$$

$$\approx \frac{\mathbf{1}}{\mathbf{4}\boldsymbol{\pi}\boldsymbol{\varepsilon}_0}\left(\frac{\boldsymbol{\mu}\mathbf{0}\cdot\boldsymbol{\mu}\mathbf{2} - \mathbf{3}(\boldsymbol{\mu}\mathbf{0}\cdot\vec{\boldsymbol{r}})(\boldsymbol{\mu}\mathbf{2}\cdot\vec{\boldsymbol{r}})}{\boldsymbol{r}^{\mathbf{3}}}\right)\left[\boldsymbol{\sigma}_-(\mathbf{t})\,\boldsymbol{a}^\dagger(\boldsymbol{t})e^{i(\omega 0-\omega 2)t} + \boldsymbol{\sigma}_+(\mathbf{t})\,\boldsymbol{a}(\boldsymbol{t})e^{-i(\omega 0-\omega 2)t}\right]$$

$$H_{res,0} = \hbar\sum_j \omega_j\left\{A_j^\dagger A_j + C_j^\dagger C_j\right\}$$

$$H_{irrev} = \hbar \sum_j \begin{Bmatrix} \sqrt{\gamma_j}\left(A_j\, \hat{a}^{\dagger} e^{-i(\omega_j-\omega_0)t} + {A_j}^{\dagger} a e^{i(\omega_j-\omega_0)t}\right) + \\ \sqrt{\gamma_{j,2}}\left(C_j\, \sigma_+ e^{-i(\omega_j-\omega_2)t} + \sigma_- {C_j}^{\dagger} a e^{i(\omega_j-\omega_2)t}\right) \end{Bmatrix} \quad (2)$$

$\Omega = \frac{\mu_2\mu_0}{4\pi\hbar r\varepsilon_0}$ is the coupling strength. μ_0 and μ_2 are the dipole matrix elements for NP and TLS, respectively. The *A*'s represent the
combined effects of electromagnetic radiation and NP thermal phonons, while the *C*'s represent the combined effects of electromagnetic radiation, thermal noise, and electronic pump noise contributing to decay and dephasing of the TLS. The decay constant γ describes the rate of spontaneous emission for the NP and also includes damping due to other sources such as Ohmic losses, while γ_2 describes decay of the TLS induced by the *C* reservoir.
The final equations of motion take the form

$$\frac{d}{dt} a = -\frac{\gamma}{2} a(t) - i\,\Omega_{int}\, e^{-i(\omega_0-\omega_2)t}\, \sigma_-(t) + F_a(t) \quad (3)$$

$$\frac{d}{dt}\sigma_-(t) = -\frac{\gamma_c}{2}\sigma_-(t) + i\Omega_{int}\,\sigma_z(t)\, a(t) e^{-i(\omega_0-\omega_2)t} + F_{c,z}(t)$$

$$\frac{d}{dt}\sigma_z(t) = -\gamma_p\, \sigma_z + 2i\Omega_{int}\left[\sigma_-(t)\, a^{\dagger}(t)\, e^{i(\omega_0-\omega_2)t} + \sigma_+(t)\, a(t)\, e^{-i(\omega_0-\omega_2)t}\right] - \gamma_2 + \frac{\Lambda_p}{2} + F_{c.z}(t)$$

The noise operators $F_a(t)$,$F_{c,z}(t)$, $F_{c.z}$ (t) have bilinear expectation values [7]. Λ_p represents the pump rate of the TLS. $\gamma_p = \gamma_c + \frac{\Lambda_p}{2}$ and $\gamma_c \equiv \gamma_2\,(2\bar{n}^c + 1)$. $\bar{n}^c$ is the average number of quanta in the *C* reservoir.

3. Threshold Conditions and The Lasing Rate

We can find the threshold conditions for the system by making the semiclassical approximation of factorizing expectation values. This is equivalent to assuming that the NP plasmons are in a coherent state.

$$\frac{d}{dt}\langle A\rangle = -\left[\frac{\gamma}{2} + i(\omega_0 - v)\right]\langle A(t)\rangle + G\langle \Sigma_z\rangle\langle A\rangle$$

$$\frac{d}{dt}\langle \Sigma_z\rangle = -\gamma_p\langle \Sigma_z\rangle - 4G\langle \Sigma_z\rangle\langle N\rangle +) + \left[-\gamma_2 + \frac{\Lambda_p}{2}\right] \quad (4)$$

In the steady-state,this has solution:

$$\langle N\rangle = \langle A^{\dagger}\rangle\langle A\rangle = \left\{\frac{1}{2\gamma}\left[\frac{\Lambda_p}{2} - \gamma_2\right] - \frac{\gamma_p}{4G}\right\} \quad (5)$$

$$\Sigma_{z0} \equiv \frac{\left[\frac{\Lambda_p}{2} - \gamma_2\right]}{\gamma_p + 4GN_0} = \frac{\gamma}{2G} \quad (6)$$

N is the plasmon number. The right side of Eq.5 must be positive, The pumping threshold condition is given by the Eq.6:

$$\Lambda_p > \left\{\frac{2\gamma\gamma_c + 4G\gamma_2}{2G - \gamma}\right\} \quad (7)$$

where $G = \frac{2{\Omega_{int}}^2}{\gamma_c}$. It can be easily shown that requiring the threshold value of Σ_{z0} to be less than 1 implies:

$$\Omega^2 > \frac{\gamma\gamma_c}{4} \quad (8)$$

4. Intensity Spectrum

In determining the intensity spectrum we will take twoapproaches. In the first we follow the usual laser model in which the phase decay of the TLS coherence is large: $\gamma_2 \gg \gamma$. In the second approach, corresponding more closely to conventional materials and technology, we assume the opposite condition $\gamma \gg \gamma_2$.

When $\gamma_2 \gg \gamma$: both σ_- , σ_z decay rapidly compared to the plasmon field and can be assumed to follow this field on time scales long compared to γ_2^{-1}.

To calculate the intensity spectrum we assume that we are far above threshold, that we can neglect the fluctuations in the amplitude inasmuch as this quantity is constrained to fluctuate about its steady-state value, while the phase can change freely [10]. We therefore consider only the time dependence in the phase. The plasmon field operator A(t) can be written classically as $\mathrm{A(t)} = \mathrm{A_0}\, \mathrm{e}^{-\mathrm{i}\emptyset}$, where A_0 is the steady state value of A given in Eq.5 and $\emptyset$ is the phase diffusion constant. The intensity is then given by the following expression:

$$\langle A(t)^{\dagger} A(0)\rangle = N_0 e^{-i\langle[\Phi(t)-\Phi(0)]\rangle} = N_0 e^{-\frac{1}{2}\langle[\Phi(t)]^2\rangle} \qquad (9)$$

Where

$$\langle D(\Phi)\rangle = \frac{1}{2}\lim_{\Delta t\to\infty}\frac{\langle[\Delta\Phi(\mathrm{t})]^2\rangle}{\Delta t}$$

The spectral width is found to be

$$\Gamma = \frac{1}{4\mathrm{N_0}}[\gamma(\bar{\mathrm{n}}_\mathrm{a} + \frac{1}{2}) + \frac{\Omega^2}{\gamma_\mathrm{c}}] \qquad (10)$$

If $\gamma \gg \gamma_2$: we can eliminate the time derivative of the Plasmon field amplitude *A*(t). This results in a set of nonlinear equations which can be solved numerically but not analytically. To increase insight into the properties of the solution, we suppose below that the population inversion of the TLS is constant. This can be justified if pumping of the TLS is sufficiently fast. Fixing the inversion allows us to solve for the spectrum exactly using the same phase diffusion technique as above. The spectral width is found to be

$$\Gamma = \frac{(2\overline{\mathrm{n}_\mathrm{a}}+1)}{8\mathrm{N_0}}\gamma \qquad (11)$$

The photon intensity spectrum is formally defined as

$$s_1(\omega, r) = \frac{A_0^2}{2\pi}(I_{NP} + I_{TLS}\, l^2)\left[\frac{1}{(\omega-\omega_0)^2+\Gamma^2}\right] \qquad (12)$$

Where

$$I_{NP} = \left|\frac{\omega_0^2}{4\pi\varepsilon_0\varepsilon_2 c^2 r}\left(\mu_0 \times \frac{\vec{r}}{r}\right)\times\frac{\vec{r}}{r}\right|^2 , I_{TLS} = \left|\frac{\omega_0^2}{4\pi\varepsilon_0\varepsilon_2 c^2 r}(\mu_2 \times \frac{\vec{r}}{r})\times\frac{\vec{r}}{r}\right|^2$$

The *I*'s are the intensities of light emitted from the uncoupled TLS and NP separately, and

$$L = \frac{2\gamma}{\Omega} \qquad (13)$$

is a constant, computed from the solution to the equations of motion.

5. Results and Analysis

To compare the DNL to typical laser, conside the cavity quality factor Q. This determined the efficiency of the cavity of the laser and is defiened by the Eq.14.

$$Q = \omega 0\ \frac{stored\ energy}{power\ loss} = \frac{\omega 0}{v} \qquad (14)$$

Where v is damping of the cavity field. The corresponding quantity entering the equations of the DNL is also $\frac{\omega 0}{\Gamma}$ where ω_0 is the optical ferequency and Γ is the decay rate of the polariton field due to ohmic and radiative mechanisms. Depending on parameter regime used, the quality factor is on the order of 10-1000. For a standard laser, the quality factor determines the photon residence time in the cavity and its inverse is therefore a measure of the laser line width. In the DNL too, the radiated spectrum have line with proportional to $\frac{1}{Q}$.

Assuming the TLS is a quantum dot, the dipole moment of the TLS and NP chosen as in Ref.[9]. The spontaneous decay of the TLS calculated a value of γ_2 on the order of 10^{11} s^{-1}[1]. The NP decay time can be taken to be around 10^{14} s^{-1} [11]. It is clear that the condition for adiabatic approximation $\gamma_2 \gg \gamma$ used in case 1, is not valid for silver particles in a silicon matrix.

The system most closely resembling a typical laser would have parameters appropriate to first case. While this does not correspond to metal NPs in a silicon matrix, it might conceivably be engineered by using kinds of materials different from those we have been considering. We choose some arbitrary numbers for γ and γ_2. we plot the spectrum for case 1 with the following parameters: n_a=0, $\gamma=10^{13}$ s^{-1}, r=50 nm, $\Lambda p=10^{13}$ s^{-1}, r_0=7 nm , $\gamma_2=10^{13}$ s^{-1} (Fig. 1).

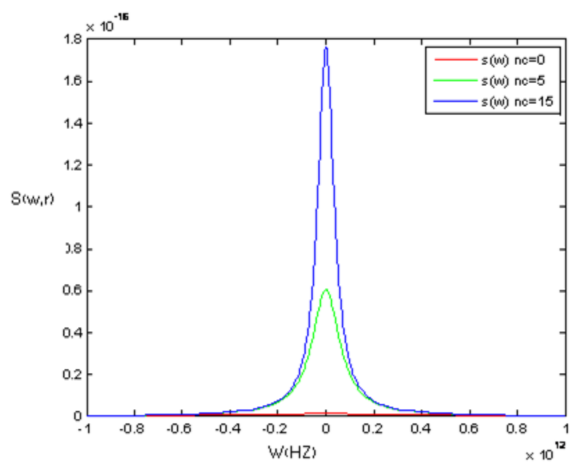

Fig 1: Spectrum of light emitted from DNL. vertical axis in units of $(Vs/m)^2$ and the electric fields are evaluated 1 μm from the TLS-NP system.

Another characteristics feauter of lasers is the line width of spectrum. It is defined as the FWHM of the intensity spectrum. Here the linewidth is about the same as for the NP, $\Gamma = 10^{12} s^{-1}$. The net result is little change. By increasing the pumping of the TLS, we see a reduction in the linewidth(Fig.2). Also increasing the noise quanta of the TLS will reduce the linewidth even more. The rate of photon emission is ΓN_0.

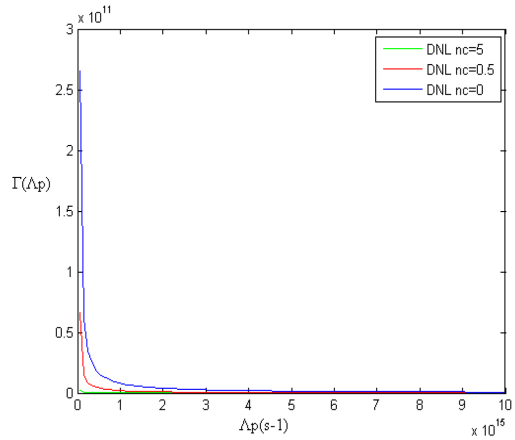

Fig 2: the depence of line width(HZ) to pumping rate(S^{-1}). By increasing the pumping of the TLS and increasing the noise quanta of the TLS, will reduce the linewidth .

For the second case, using parameters suitable to metal nanoparticles such as silver in a silicon matrix. for case 2 with the following parameters: n_a=0 and n_c=0, $\gamma=10^{14}\,s^{-1}$, r=50 nm, $\Lambda p=10^{13}\ s^{-1}$, a=7 nm,$\gamma_2=10^{11}\ s^{-1}$. (Fig.3). As in case 1,the line width can be reduced by increasing the pumping and the noise quanta of the TLS(Fig.4) .

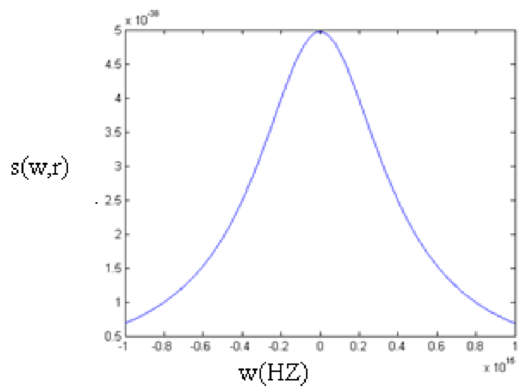

Fig 3: Spectrum of light emitted from DNL. vertical axis in units of $(Vs/m)^{2}$ and the electric fields are evaluated 1 μm from the TLS-NP system.

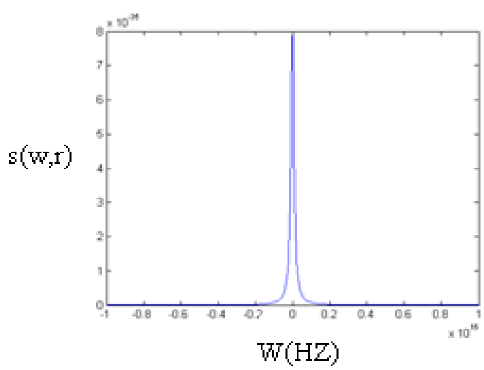

Fig 4: The reduced spectral width of the light emitted by the system for case 2 when *nc*=15. Units are same as those in Fig.3.

We also realize that the maximum of S_1 for case 2 is on the order of 10^{-35} $(Vs/m)^2$, which is 10^8 times smaller than the intensity produced in the first case.
Intensity spectrum of light emitted from DNL is higher than to thresholdless laser(see Eq.56 of [10]). We note a critical different between ordinary laser light (see Eq.57 of [7]) and the light radiated by DNL: the spectral width is much larger for the latter system, since γ is so much larger(Fig.5,6).

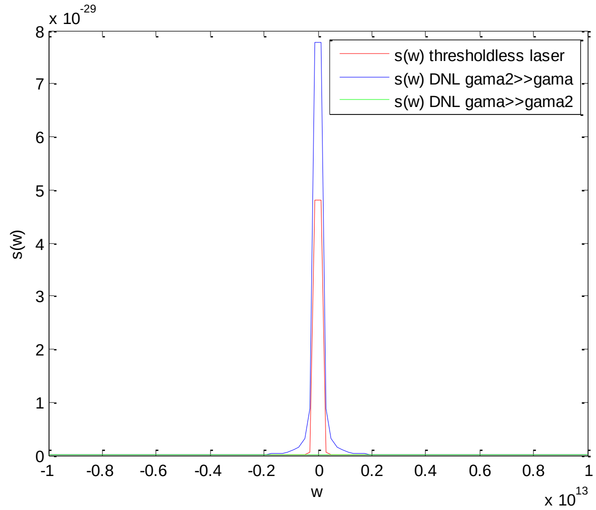

Fig 5: Intensity spectrum of light emitted from DNL is higher than to typical laser. Units are same as those in Fig.2.

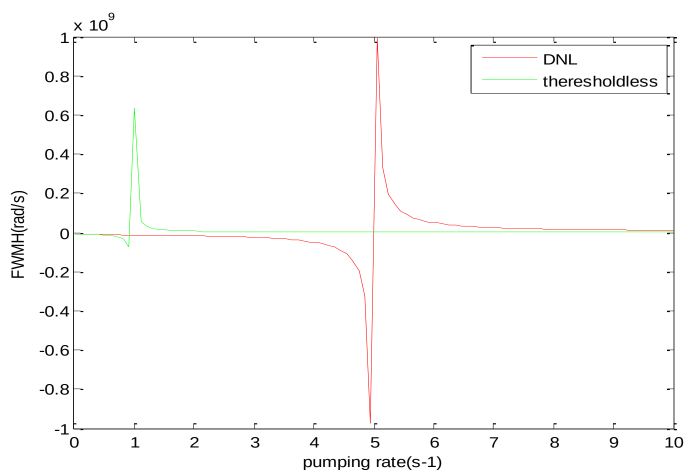

Fig 6: linewidth of light emitted from DNL case 1 is higher than to typical laser. But, in DNL the line width can be reduced by increasing the pumping and the noise quanta of the TLS

6. Conclusions

The advantage of using the dipole nanolaser over simply a pumped TLS is the strong mutual interaction of TLS and NP, which greatly increases the radiant efficiency of the system.
enhanced efficiency at least when operating with metal NPs in a silicon matrix is a broad spectrum. Another result of this work is the prediction of a narrow regime of parameters as in case 1. This light in general has a very wide frequency rang, but in principle, and for specific material, the line width can be reduced 100 below than the natural line width of the NP.

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