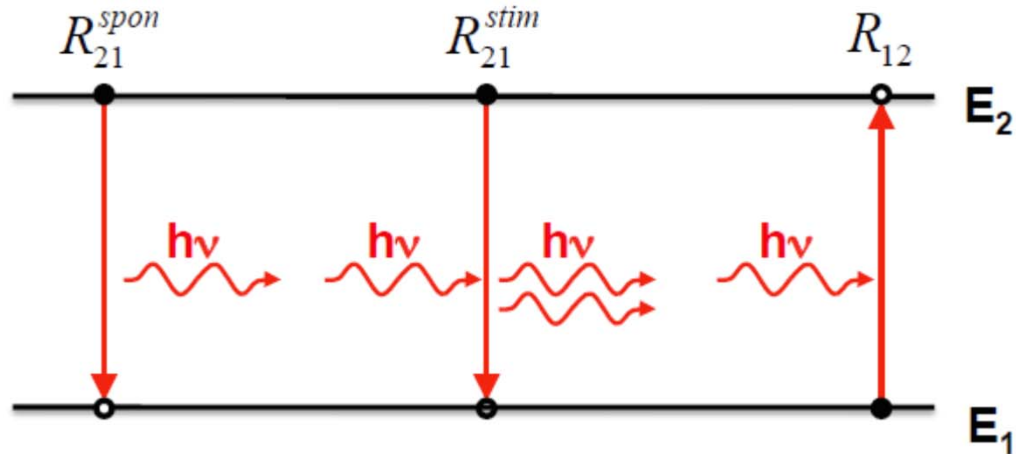
Einstein’s AB Coefficients

Einstein's AB Coefficients

$$\boxed{\begin{aligned} R_{21}^{spon} &= A_{21} f_2 \left(1 - f_1\right) \\ R_{21}^{stim} &= B_{21} f_2 \left(1 - f_1\right) P(E_{21}) \\ R_{12} &= B_{12} f_1 \left(1 - f_2\right) P(E_{21}) \end{aligned}}$$



For non-monochromatic light:

$P(E_{21}) = n_{ph} N(E_{21})$:

number of photons per unit volume per energy interval

$$n_{ph} = \frac{1}{e^{\hbar\omega_k / k_B T} - 1}$$: Number of photons per state (Bose-Einstein distribution)

$$N\left(E_{21}\right) = \frac{8\pi n_r^3 E_{21}^2}{h^3 c^3}$$:Number of states with photon energy E_{ba} per unit volume,

per energy interval

Photon Density of States

Optical wave $e^{i\vec{k}\cdot\vec{r}}$ satisfies periodic boundary condition

$\omega_k = \dfrac{kc}{n_r}$ dispersion relation of photons

(equivalent to energy band structure of electrons)

Number of states with photon energy E_{21} per unit volume, per energy interval

$$N\left(E_{21}\right) = \frac{2}{V}\int \frac{4\pi k^2 dk}{\left(\frac{2\pi}{L}\right)^3}\cdot\delta(E_{21} - \hbar\omega_k)$$

$$= \frac{8\pi}{\left(2\pi\right)^3}\int\left(\frac{n_r\omega_k}{c}\right)^2 \frac{n_r}{c}d\omega_k \cdot \frac{1}{\hbar}\delta(\frac{E_{21}}{\hbar} - \omega_k)$$

$$\boxed{N\left(E_{21}\right) = \frac{8\pi n_r^3 E_{21}^2}{h^3 c^3}}$$

Einstein's AB Coefficients

At thermal equilibrium:

$$R_{12} = R_{21}^{spon} + R_{21}^{stim}$$

$$B_{12} f_1 \left(1 - f_2\right) P(E_{21}) = A_{21} f_2 \left(1 - f_1\right) + B_{21} f_2 \left(1 - f_1\right) P(E_{21})$$

$$P(E_{21}) = \frac{A_{21} f_2 \left(1 - f_1\right)}{B_{12} f_1 \left(1 - f_2\right) - B_{21} f_2 \left(1 - f_1\right)} = \frac{A_{21} e^{\frac{E_1 - F}{k_B T}}}{B_{12} e^{\frac{E_2 - F}{k_B T}} - B_{21} e^{\frac{E_1 - F}{k_B T}}}$$

$$N(E_{21}) \cdot n_{ph} = \frac{A_{21}}{B_{12} e^{\frac{E_2 - E_1}{k_B T}} - B_{21}} \quad \Rightarrow \quad \left(\frac{8\pi n_r^3 E_{21}^2}{h^3 c^3}\right) \frac{1}{e^{h\omega_k / k_B T} - 1} = \frac{A_{21}}{B_{12} e^{\frac{E_2 - E_1}{k_B T}} - B_{21}}$$

$$\boxed{\begin{array}{l} B_{12} = B_{21} \\ \dfrac{A_{21}}{B_{21}} = \dfrac{8\pi n_r^3 E_{21}^2}{h^3 c^3} = N(E_{21}) \end{array}}$$

Spontaneous Emission Spectra

$$B_{12} = B_{21} = B$$

$$\frac{A_{21}}{B} = \frac{8\pi n_r^3 E_{21}^2}{h^3 c^3} = N(E_{21})$$

$$R_{21}^{spon} = r_{21}^{spon}(E_{21})dE = A_{21} f_2 (1 - f_1)$$

$$R_{net}^{abs} = r_{net}^{abs}(E_{21})dE = B\left[f_1 - f_2\right]P(E_{21})$$

Absorption coefficient:

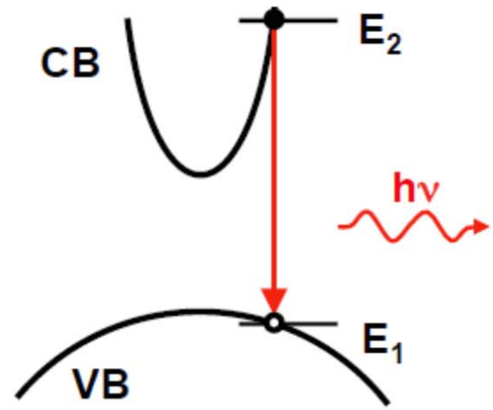
$$\alpha(E_{21})dE = \frac{r_{net}^{abs}(E_{21})dE}{P(E_{21})(c/n_r)} = \frac{n_r}{c} B\left[f_1 - f_2\right] = -g(E_{21})dE$$

$$\frac{r_{21}^{spon}(E_{21})}{g(E_{21})} = \frac{A_{21}}{\frac{n_r}{c}B} \underbrace{\left[\frac{f_2(1-f_1)}{f_2 - f_1}\right]}_{n_{sp}}$$

$$r_{21}^{spon}(E_{21}) = \frac{8\pi n_r^2 E_{21}^2}{h^3 c^2} \underbrace{\left[\frac{1}{1 - e^{\frac{E_{21} - \Delta F}{k_B T}}}\right]}_{n_{sp}} g(E_{21}) \qquad [\frac{1}{s}\frac{1}{m^3}\frac{1}{eV}]$$

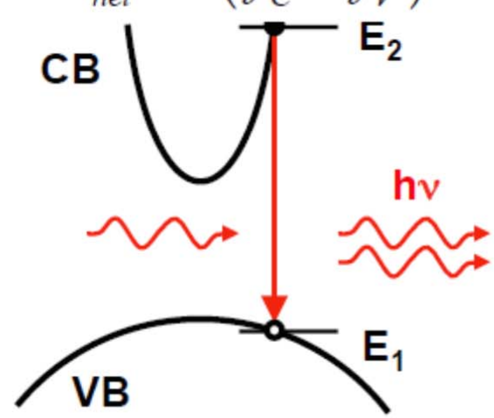
Spontaneous Emission

$$R^{spon} \propto f_C\left(1 - f_V\right)$$

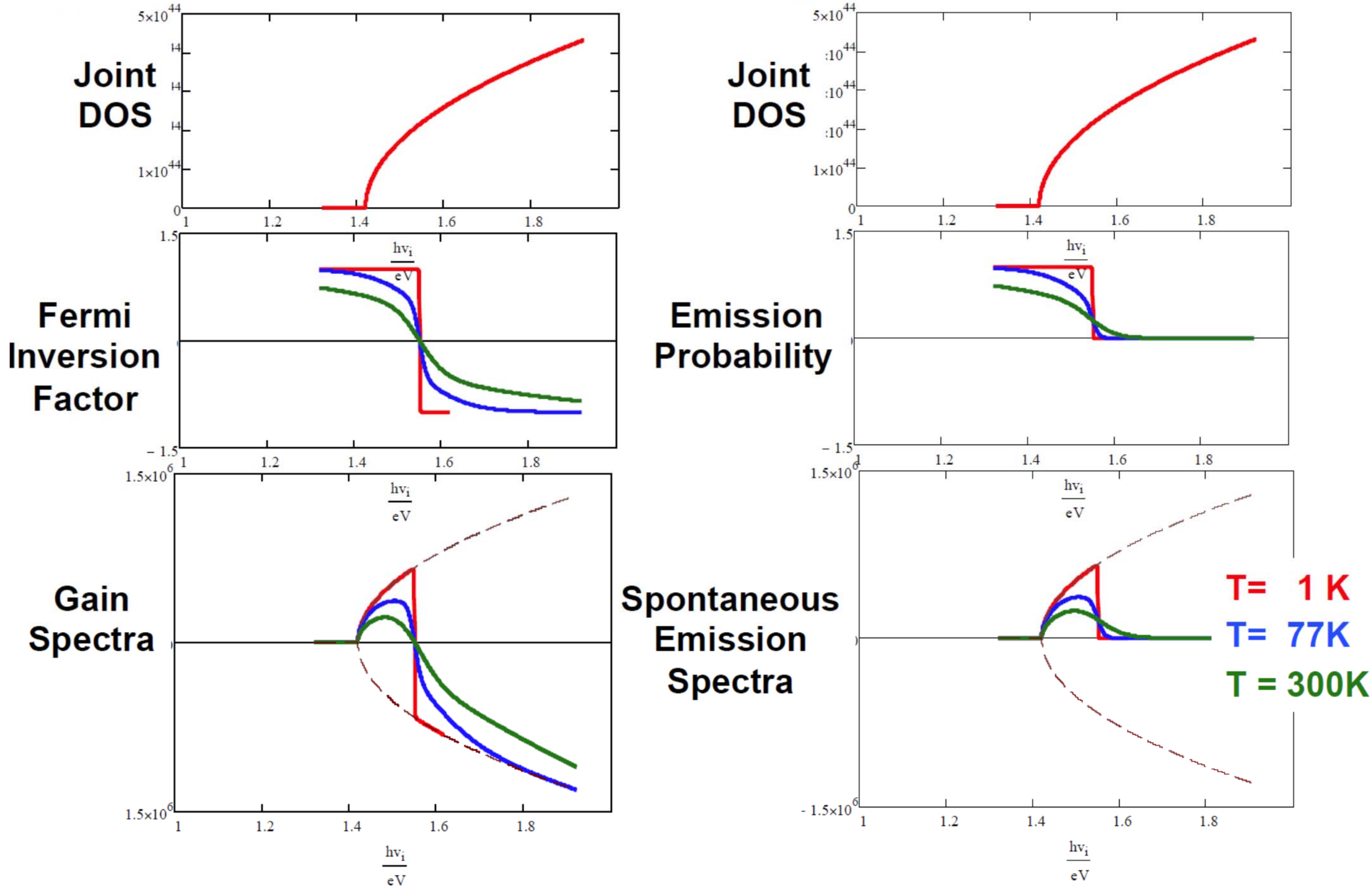


Stimulated Emission

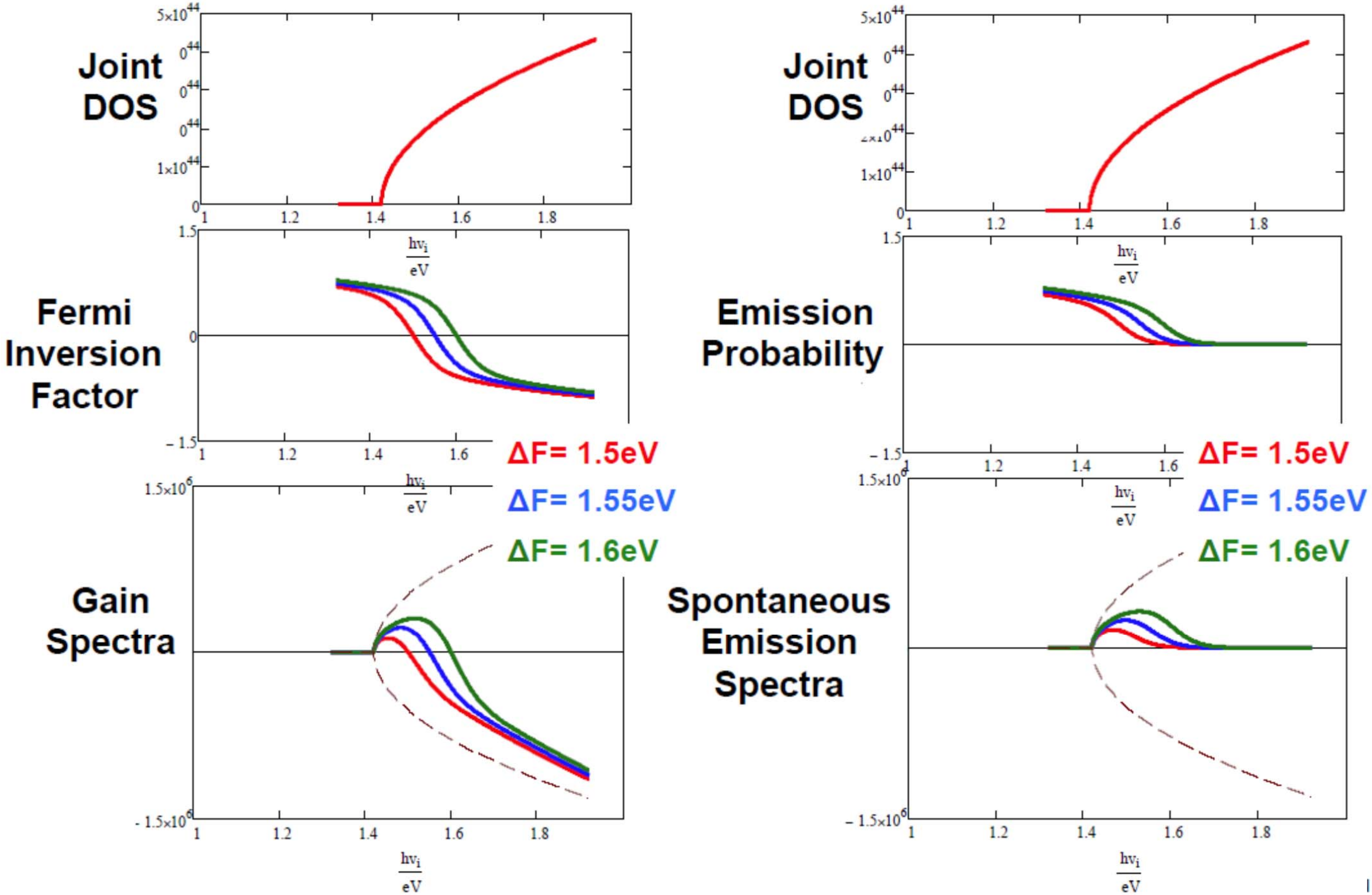
$$R_{net}^{stim} \propto \left(f_C - f_V\right)$$



Spontaneous Emission and Gain Spectra for Various Temperatures



Spontaneous Emission and Gain Spectra for ΔF (T = 300 K)



Spontaneous Emission Lifetime

$$r_{21}^{spon}(\hbar\omega) = \frac{1}{\tau_r}\rho_r(\hbar\omega - E_g) f_e(\hbar\omega)$$

$$f_e(\hbar\omega) = f_C(E_2)\left(1 - f_V(E_1)\right)$$

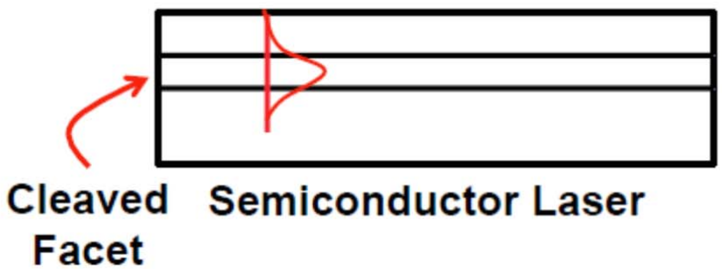
$$r_{21}^{spon}(E_{21}) = \frac{8\pi n_r^2 E_{21}^2}{h^3 c^2} \frac{1}{1 - e^{\frac{E_{21}-\Delta F}{k_B T}}} g(E_{21})$$

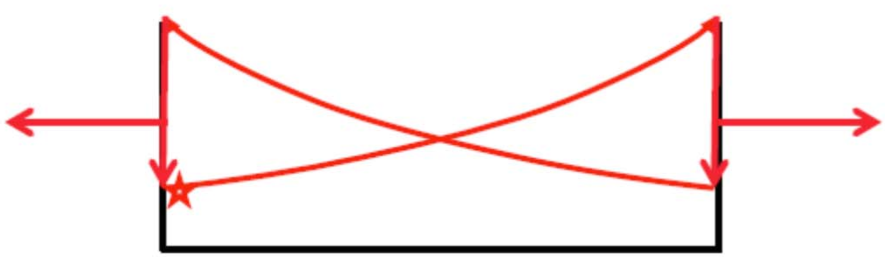
$$= \frac{8\pi n_r^2 E_{21}^2}{h^3 c^2} \frac{f_e(\hbar\omega)}{f_g(\hbar\omega)} \left(C_0 \left| \hat{e} \cdot \vec{P}_{cv} \right|^2 \rho_r(\hbar\omega - E_g) \right)$$

$$\Rightarrow \tau_r = \frac{h^3 c^2}{8\pi n_r^2 E_{21}^2} \cdot \frac{1}{C_0 \left| \hat{e} \cdot \vec{P}_{cv} \right|^2} f_g(\hbar\omega)$$

Typically $\tau_r \sim 1$ nsec

Basic Concept of Lasers

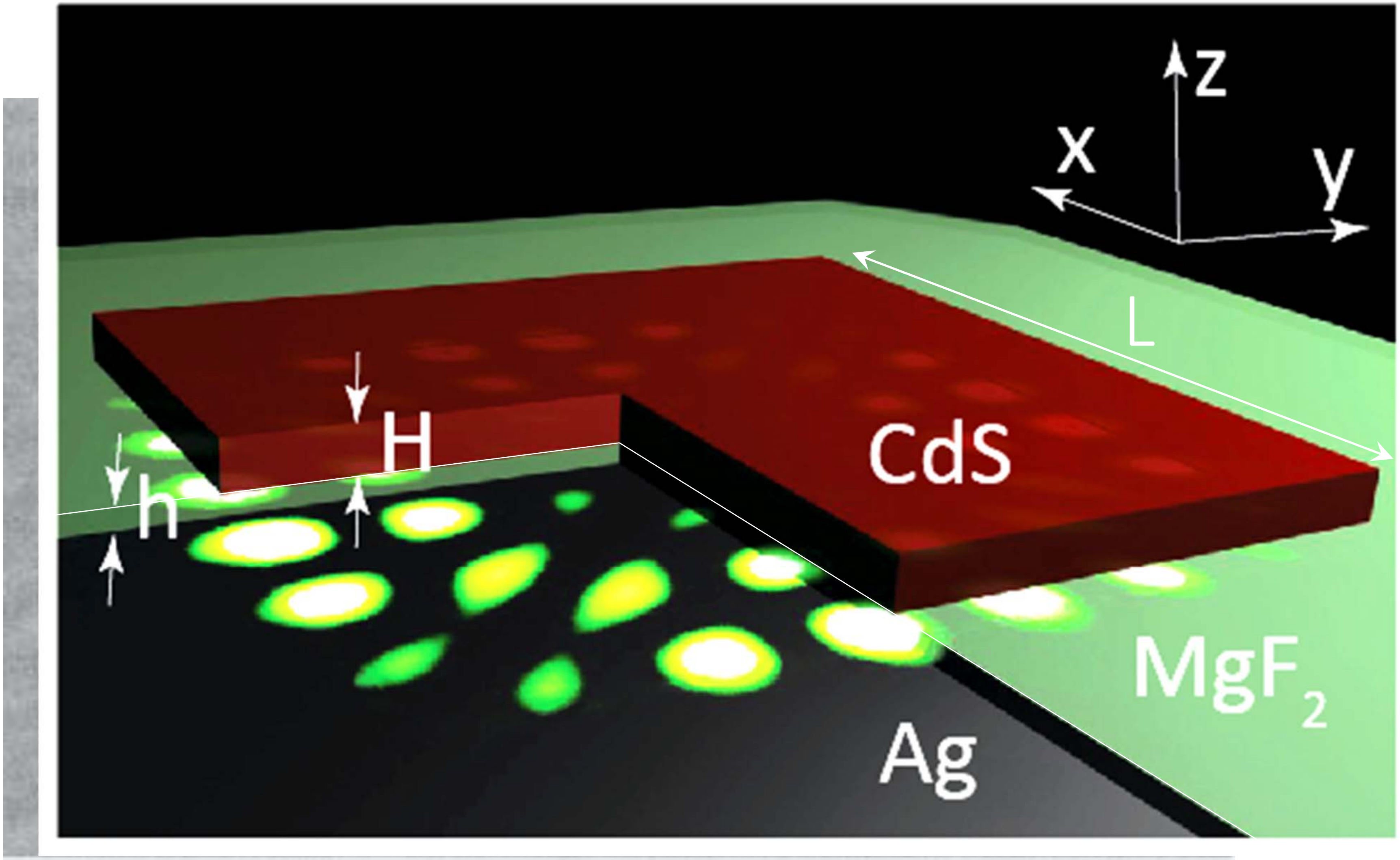




- Laser:
  - Light Amplification by Stimulated Emission of Radiation
- Basic elements:
  - Gain media
  - Optical cavity
- Threshold condition:
  - Bias point where laser starts to “lase”
  - Gain (nearly) equals loss

An example

Square plasmon laser



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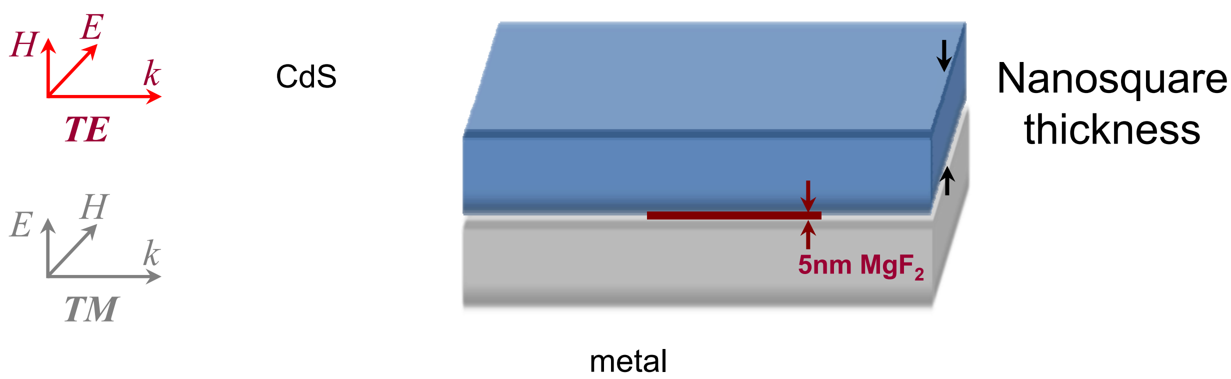
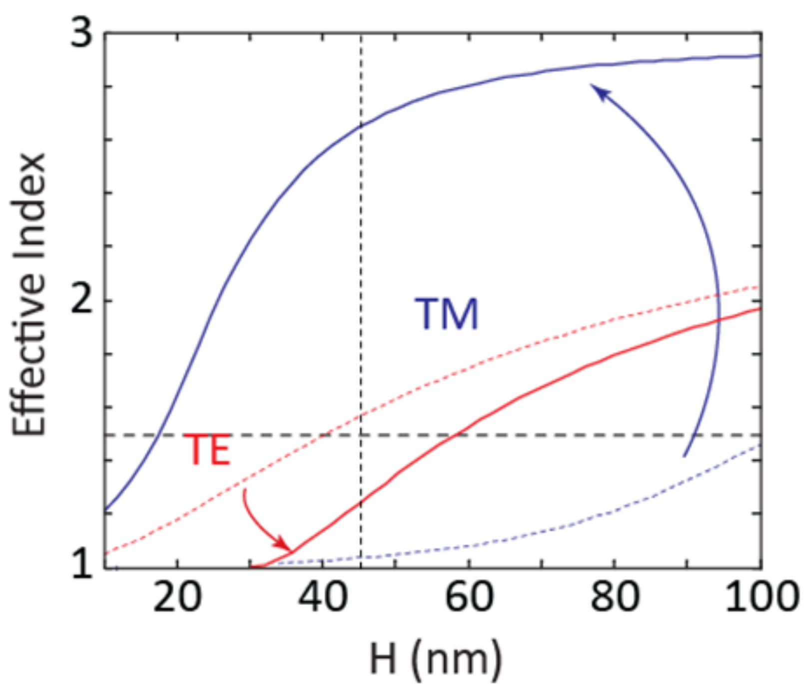
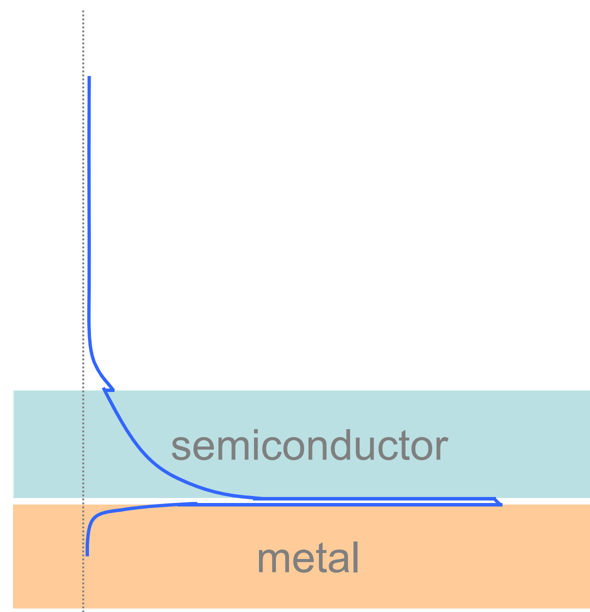
Metal-Insulator-Semiconductor Surface Plasmon Mode

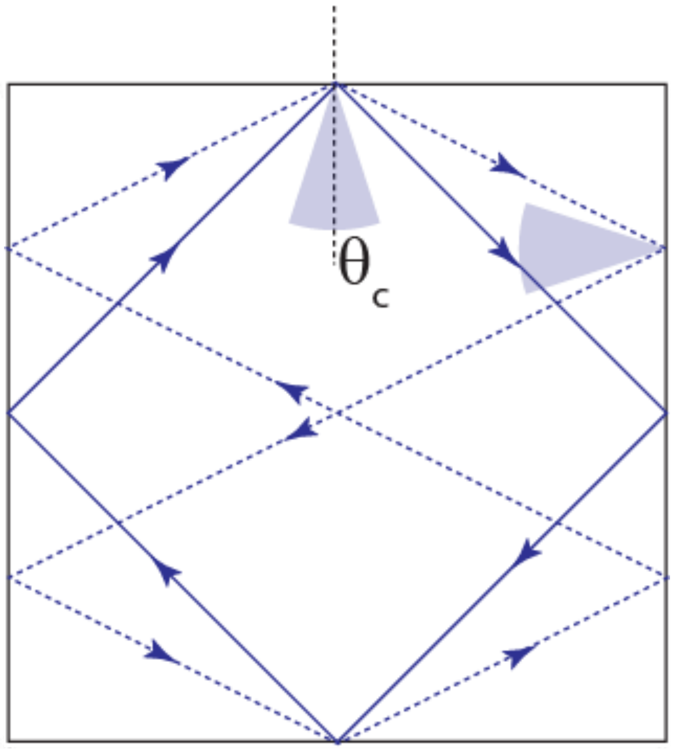


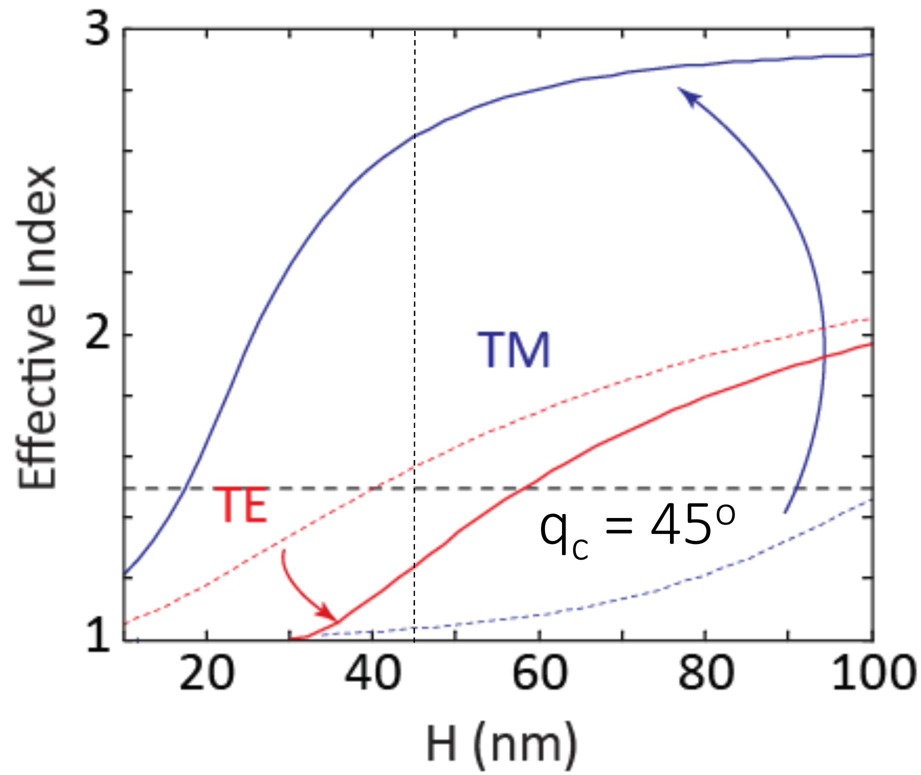




Total internal reflection of surface plasmons

Radiation loss: 1.6×10^4/cm → 500/cm





Photonic mode can NOT lase

Plasmon mode has lower loss than photonic mode

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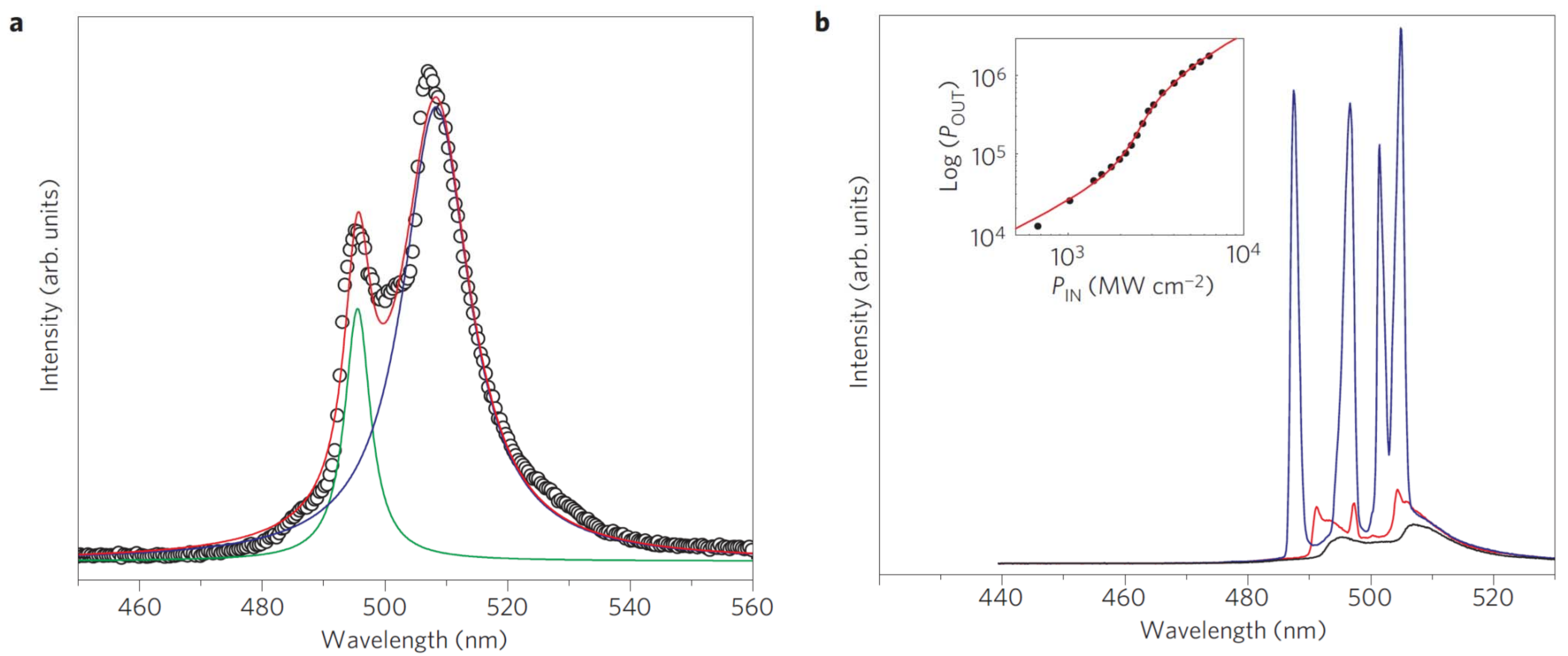
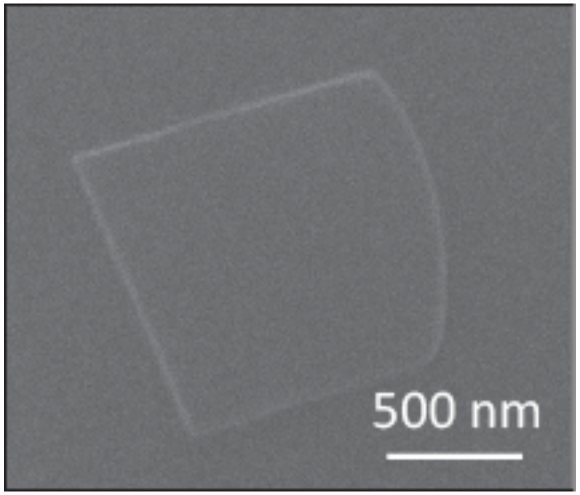
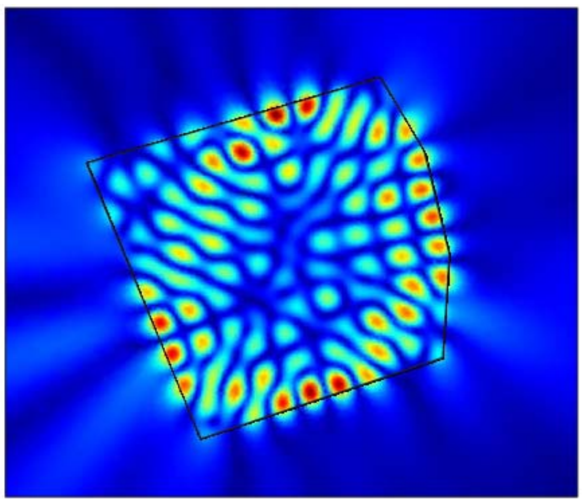
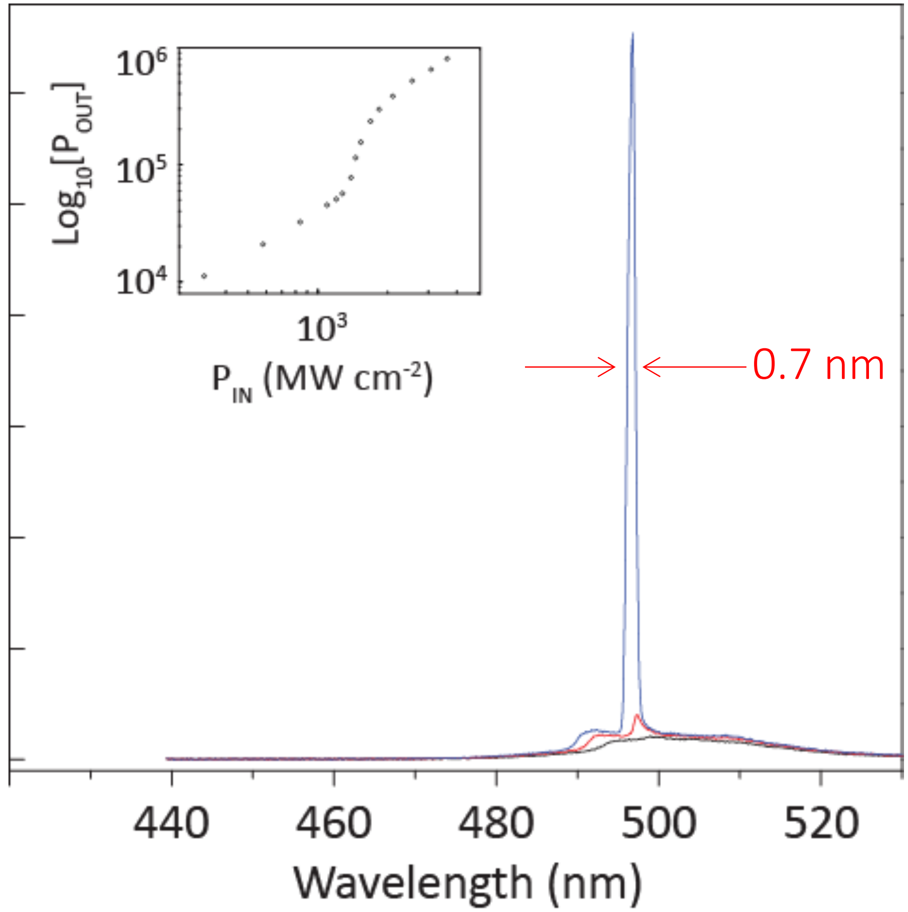
Emission of square plasmon laser



Single mode plasmon laser







Room temperature, single mode

Plasmon mode has lower loss than photonic mode

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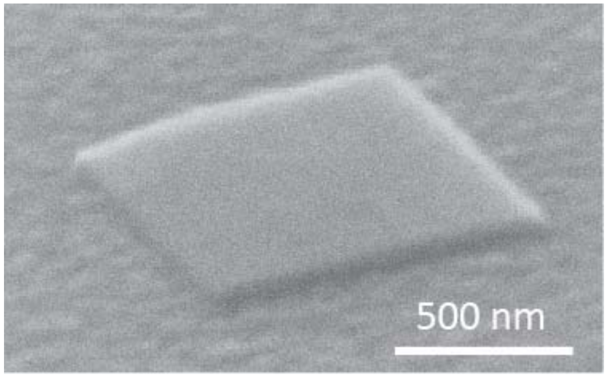
Purcell effect in plasmon cavities



- How does strongly confined light interact with matter?
  - It substantially modifies the rate of spontaneous emission

Fermi's Golden Rule:

$$\frac{1}{\tau_{sp}} = \frac{2\pi}{\hbar^2} \left\langle f \middle| d \cdot E \middle| i \right\rangle^2 \rho(\omega)$$

Field Enhancement

Modified PDOS