Valencia Nanophotonics Technology Center

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UNIVERSIDAD POLITECNICA DE VALENCIA

Theoretical study of the emission of light in indirect bandgap semiconductor stimulated by phonons

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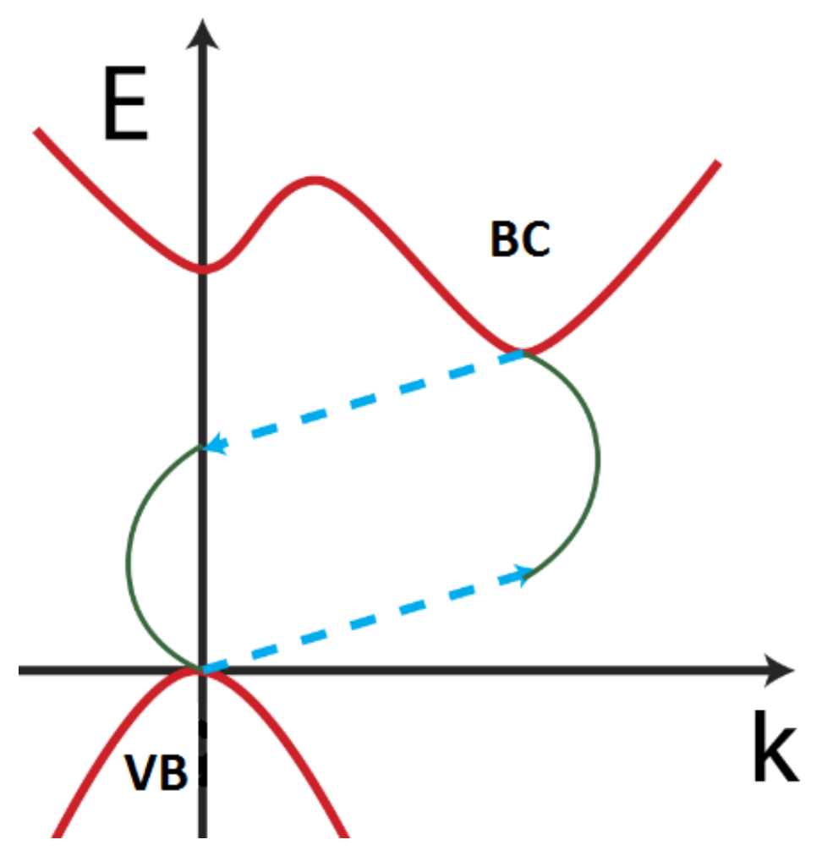
Introduction



Silicon laser: “holy grail” of optical communications

The main roadblock is the fact that the silicon has an indirect energy bandgap and, therefore, it is highly inefficient as a light source

A phonon of the right energy and momentum is required to produce the transition from the conduction band (CB) to the valence band (CV)

Einstein’s coefficients for indirect gap semiconductors

R_{kq} = Stimulated emission of photons and phonons

R_{k0} = Stimulated emission of photons and spontaneous emission of phononses

R_{0q} = Spontaneous emission of photons and stimulated emission of phonons

R_{00} = Spontaneous emission of photons and phonons

At thermodynamic equilibrium must be fulfilled

$$R_{kq}+R_{k0}+R_{0q}+R_{00}=R_{ab}$$

$$n_p=\frac{D_p}{e^{\frac{\hbar\omega}{K_bT}}-1}\qquad n_q=\frac{1}{e^{\frac{\hbar\Omega}{K_bT}}-1}$$

$$1+\frac{B_{k0}}{B_{kq}}=1\rightarrow\quad B_{k0}=0$$

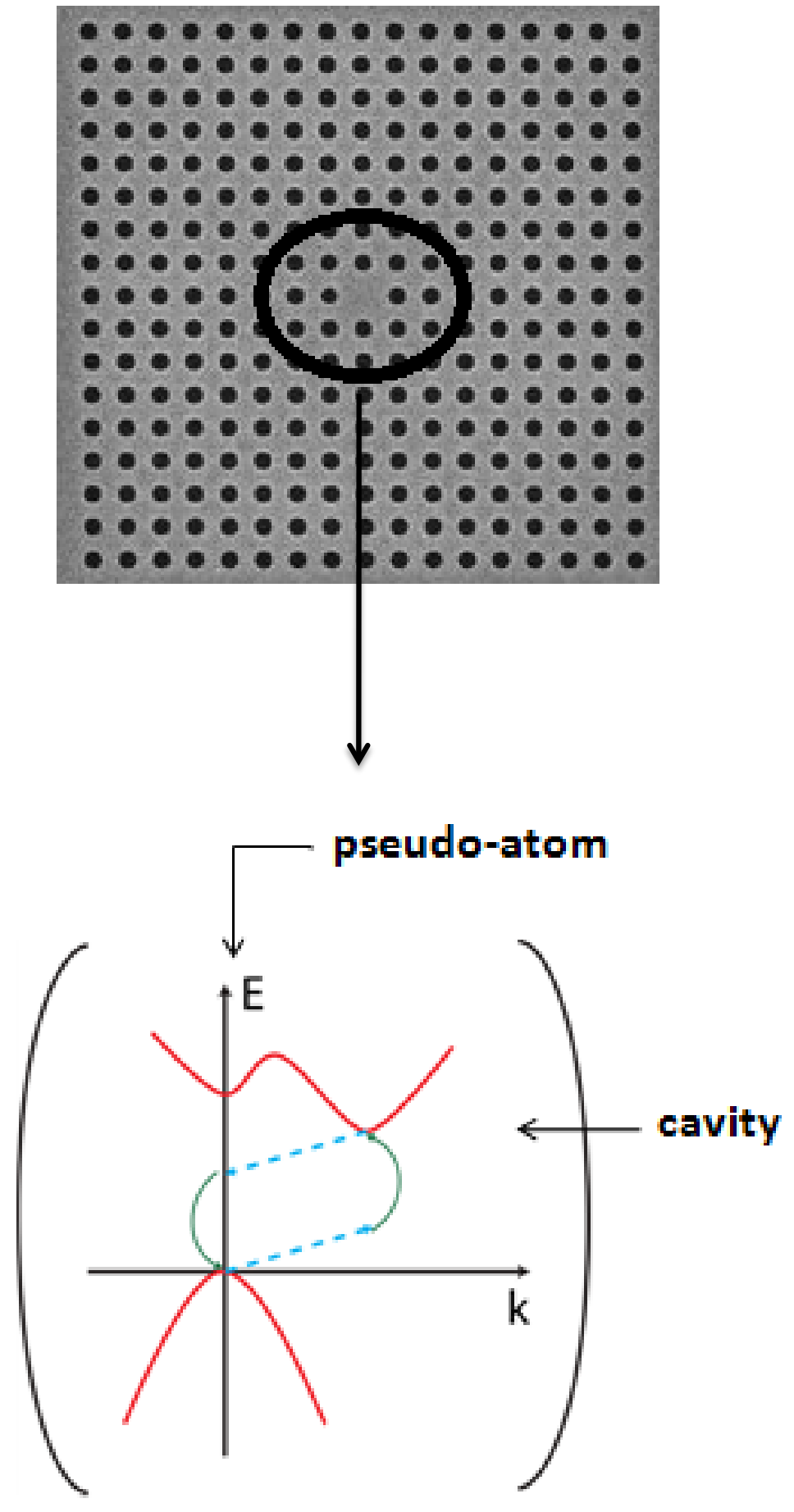
$$B_{ab}=B_{kq}$$

$$B_{0q}(n_q+1)+B_{00}=D_pB_{kq}(n_q+1)\rightarrow\quad B_{00}=0$$

Our work	Einstein's work
$B_{ab}=B_{kq}$	$B_{cv}=B_{vc}$
$B_{0q}=D_pB_{kq}$	$A_{cv}=D_pB_{cv}$

Jaynes-Cumming model of silicon phoxonic crystal cavity

$$H=\hbar\omega_0\hat{\sigma}_{ee}+\hbar\omega_\gamma a^+a+\hbar\omega_\Omega b^+b-\hbar g\left(\hat{\sigma}_{ge}ab+\hat{\sigma}_{eg}a^+b^+\right)$$



$$\left|n-1;m-1;e\right\rangle\rightarrow\left|n;m;g\right\rangle\ \Rightarrow\ P_{ge}(t)=\frac{R_{nm}^2}{\Omega_{nm}^2}\sin^2\left(\frac{\Omega_{nm}t}{2}\right)$$

$$\left|\left|n;m;g\right\rangle\rightarrow n-1;m-1;e\right\rangle\ \Rightarrow\ P_{eg}(t)=\frac{R_{nm}^2}{\Omega_{nm}^2}\sin^2\left(\frac{\Omega_{nm}t}{2}\right)$$

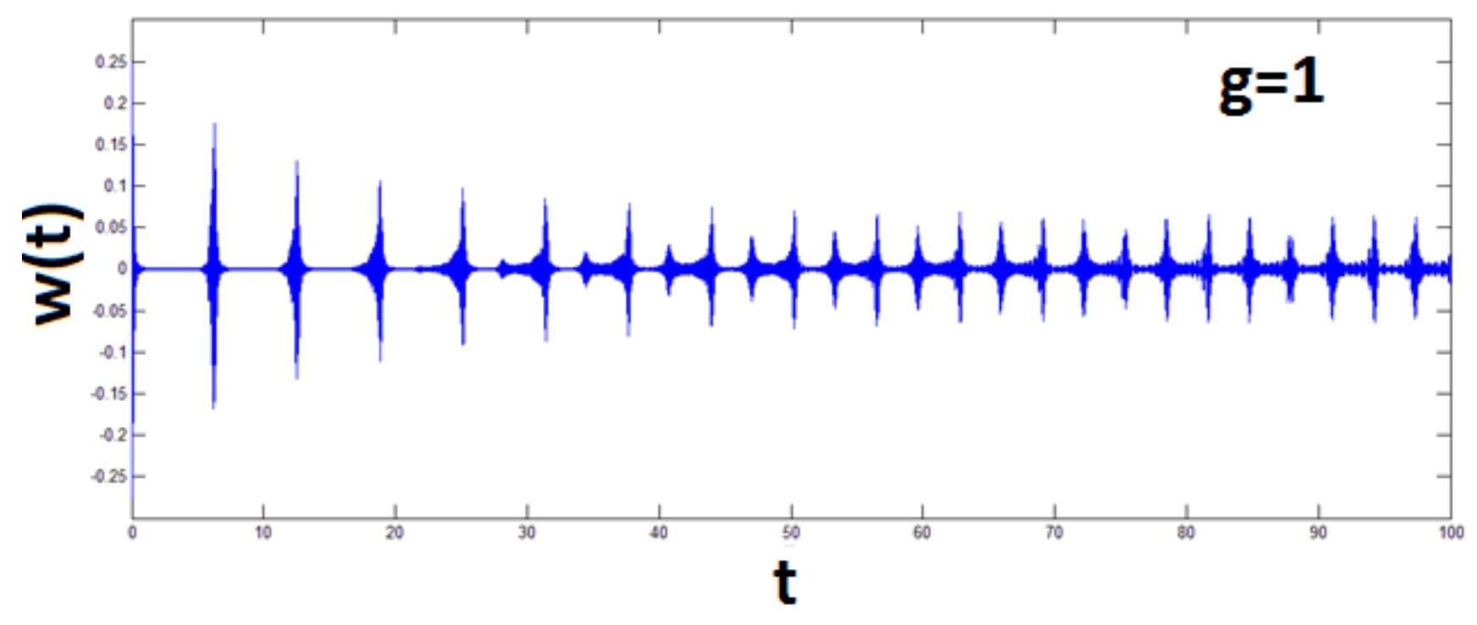
$$R_{nm}=2g\sqrt{nm}\ ;\ \Delta=\omega_0-\omega_0-\omega_0\ ;\ \Omega_{nm}=\sqrt{R_{nm}^2+\Delta^2}$$

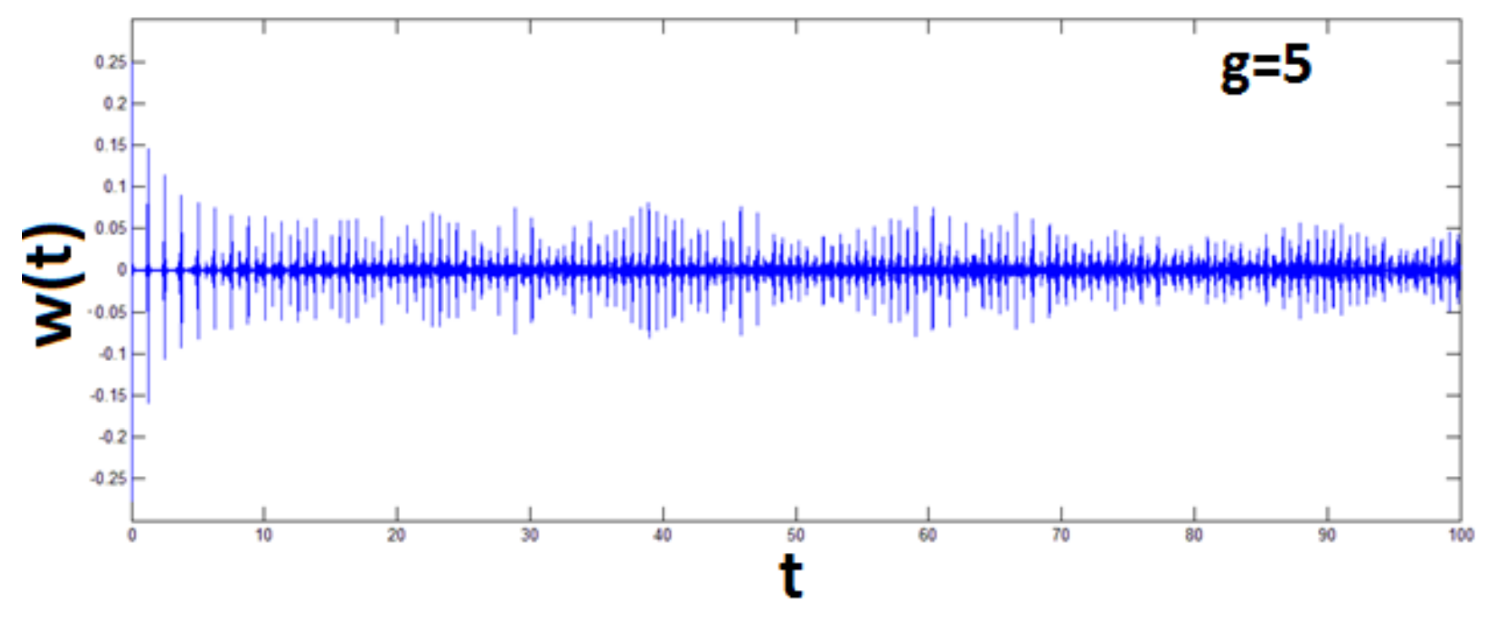
$$\left|\Psi(0)\right\rangle=\left|\alpha\right\rangle\otimes\left|\beta\right\rangle\otimes\left|n;m;g\right\rangle$$

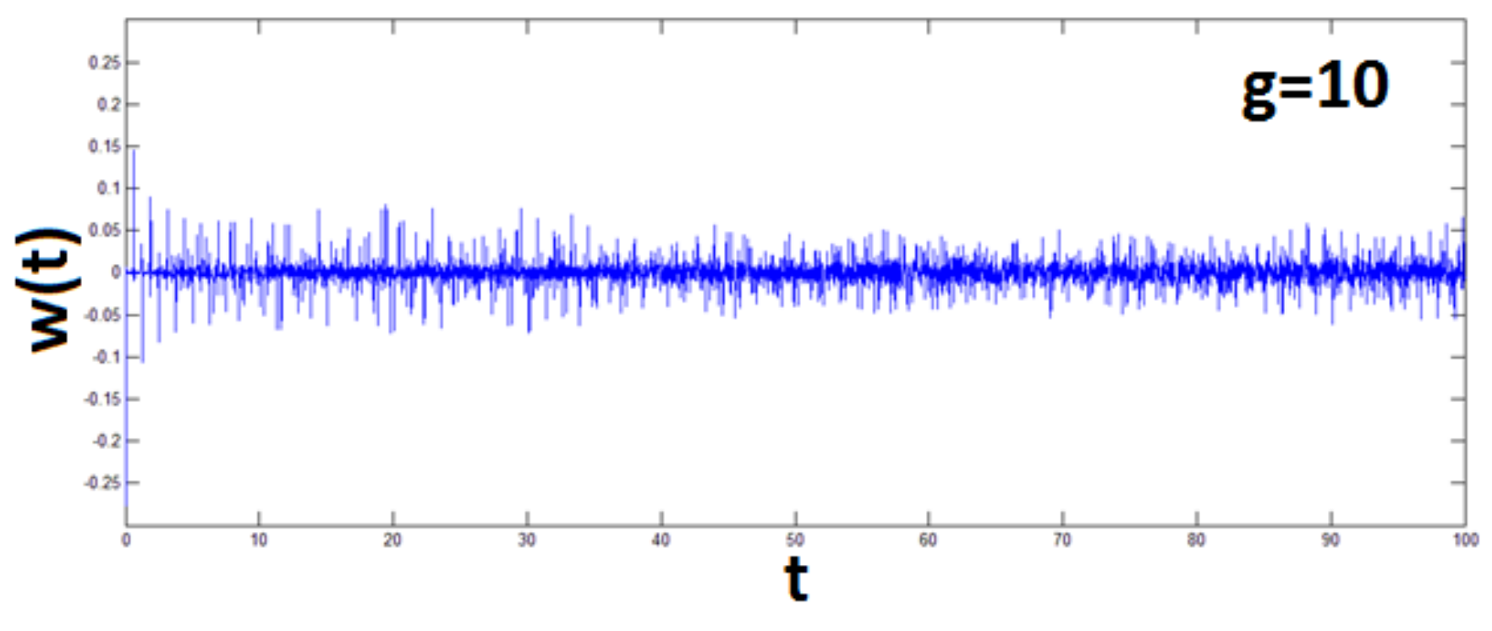
$$P_e(t)=\sum_n\sum_m\left\langle n;m;e\middle|\Psi(t)\right\rangle\ ;\ P_g(t)=1-P_e(t)$$

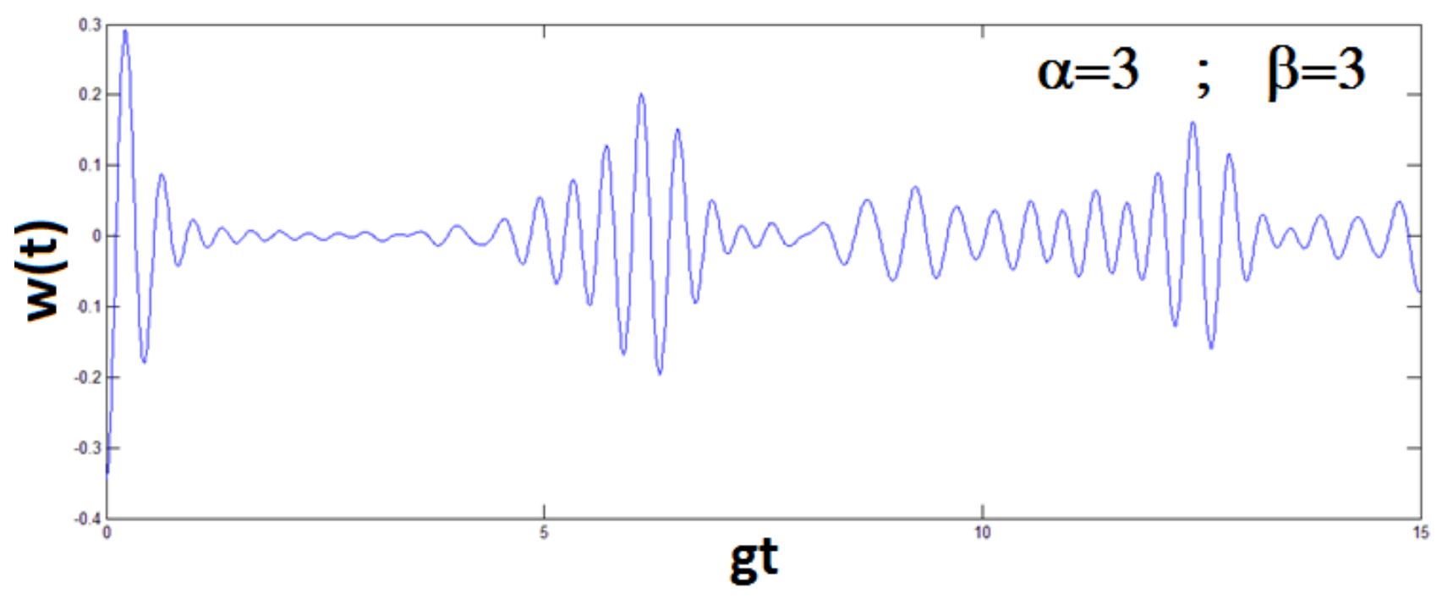
$$W(t)=P_e(t)-P_g(t)=-\sum_n\sum_m p_\alpha(n)p_\beta(n)\cos\left(\Omega_{nm}t\right)$$

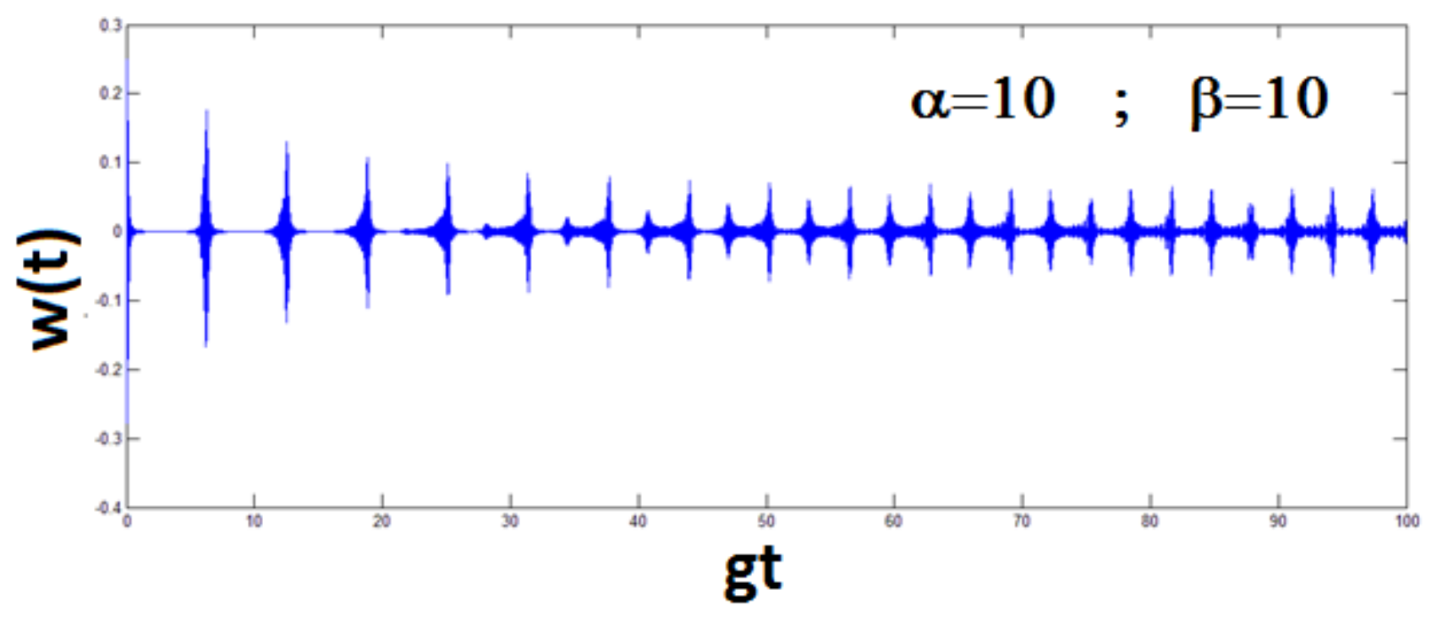
$$\left\langle n\right\rangle=\left|\alpha\right|^2\ ;\ \left\langle m\right\rangle=\left|\beta\right|^2$$











$$\tau_{col}\propto\frac{1}{g}\ ;\ \tau_{rev}\propto\frac{1}{g}$$

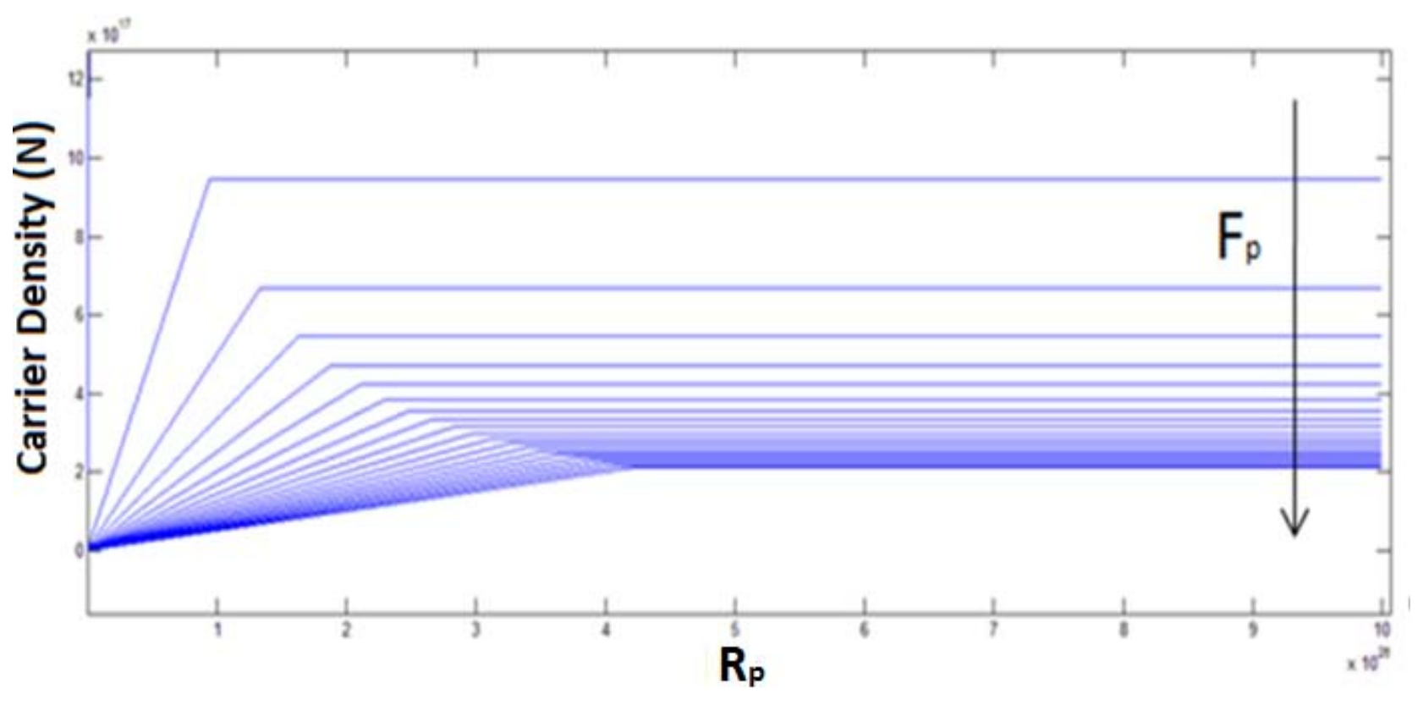
Optical gain and the Purcell Effect

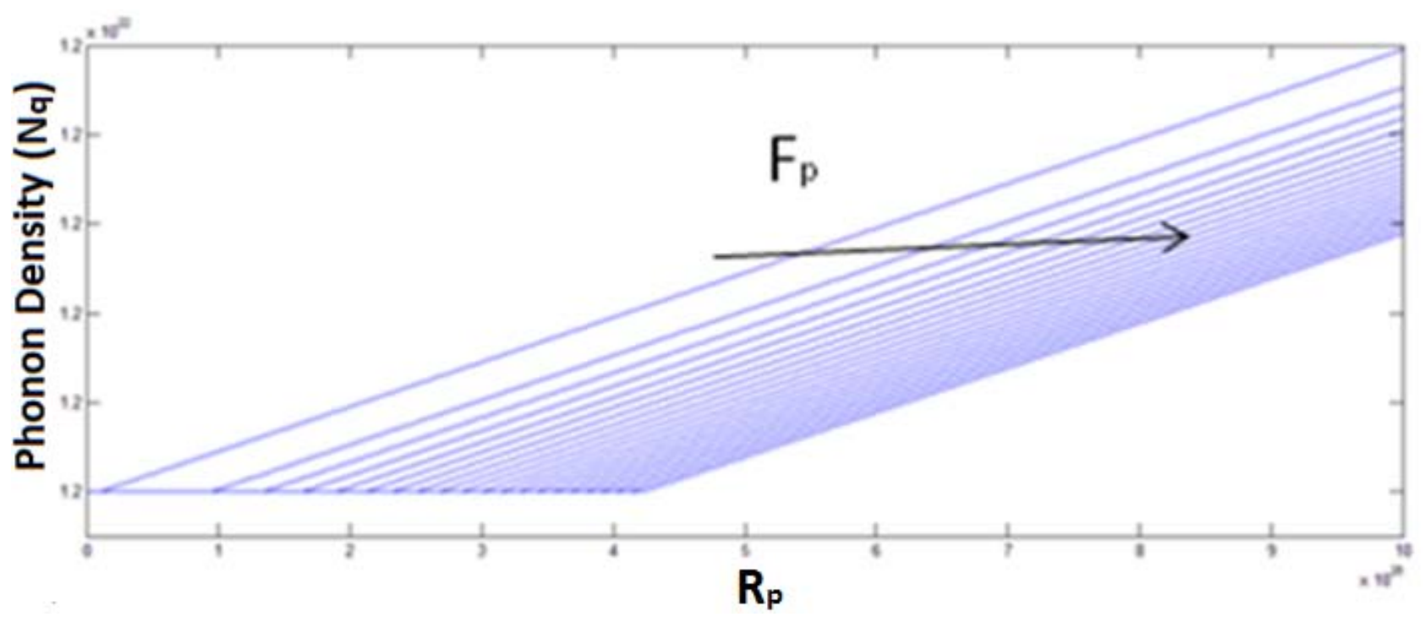
The rate of spontaneous emission depends partly on the environment of a light source (excited atom). This means that by placing the light source in a special environment, the rate of spontaneous emission can be modified

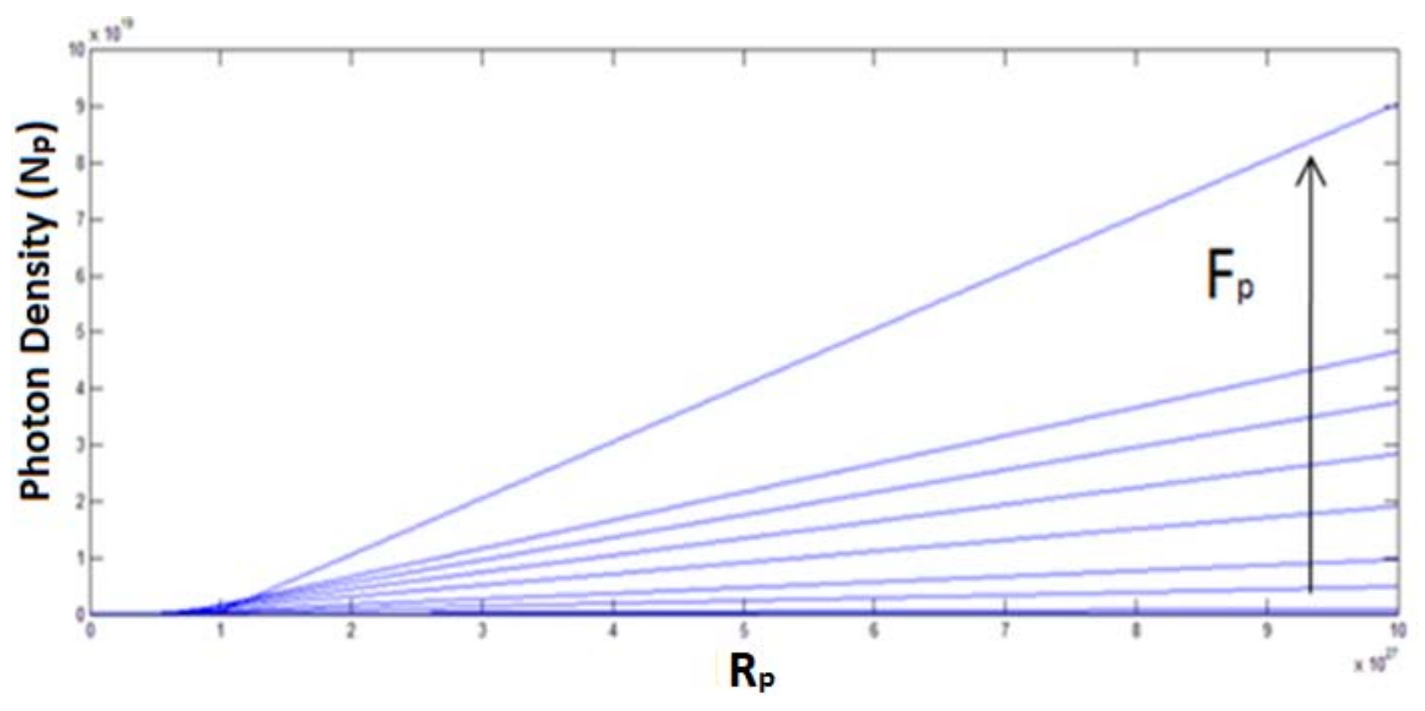
$$\mathrm{B}_{\mathrm{sp,cav}}=\mathrm{F_P}\mathrm{B}_{\mathrm{sp,bulk}}\qquad \mathrm{K}_{\mathrm{p,cav}}=F_P\mathrm{K}_{\mathrm{p,bulk}}$$

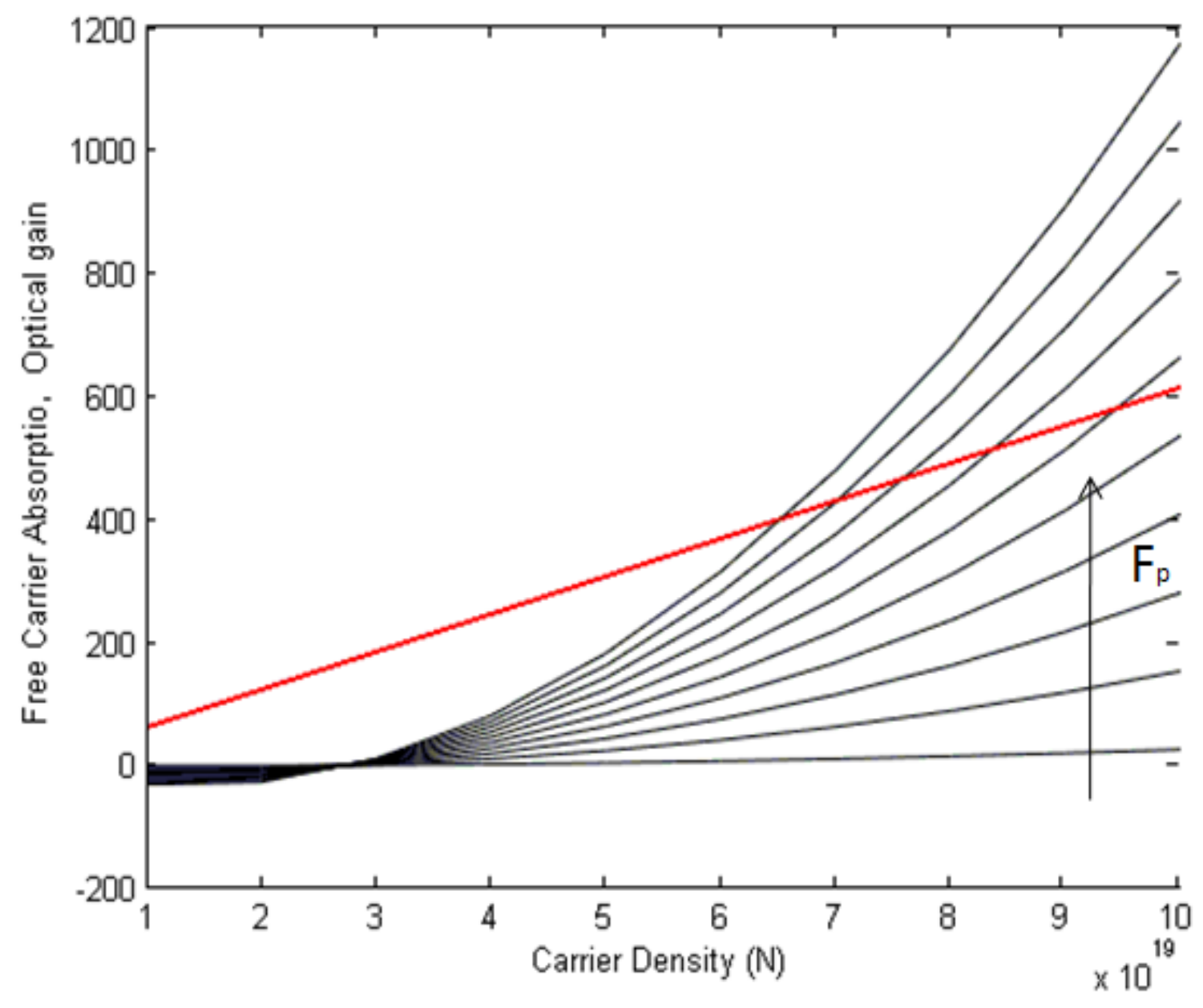
$$\tau_{\mathrm{p,cav}}=F_P\tau_{\mathrm{p,bulk}}\qquad \tau_{\mathrm{C,cav}}=\frac{\tau_{\mathrm{C,bulk}}}{F_P}$$

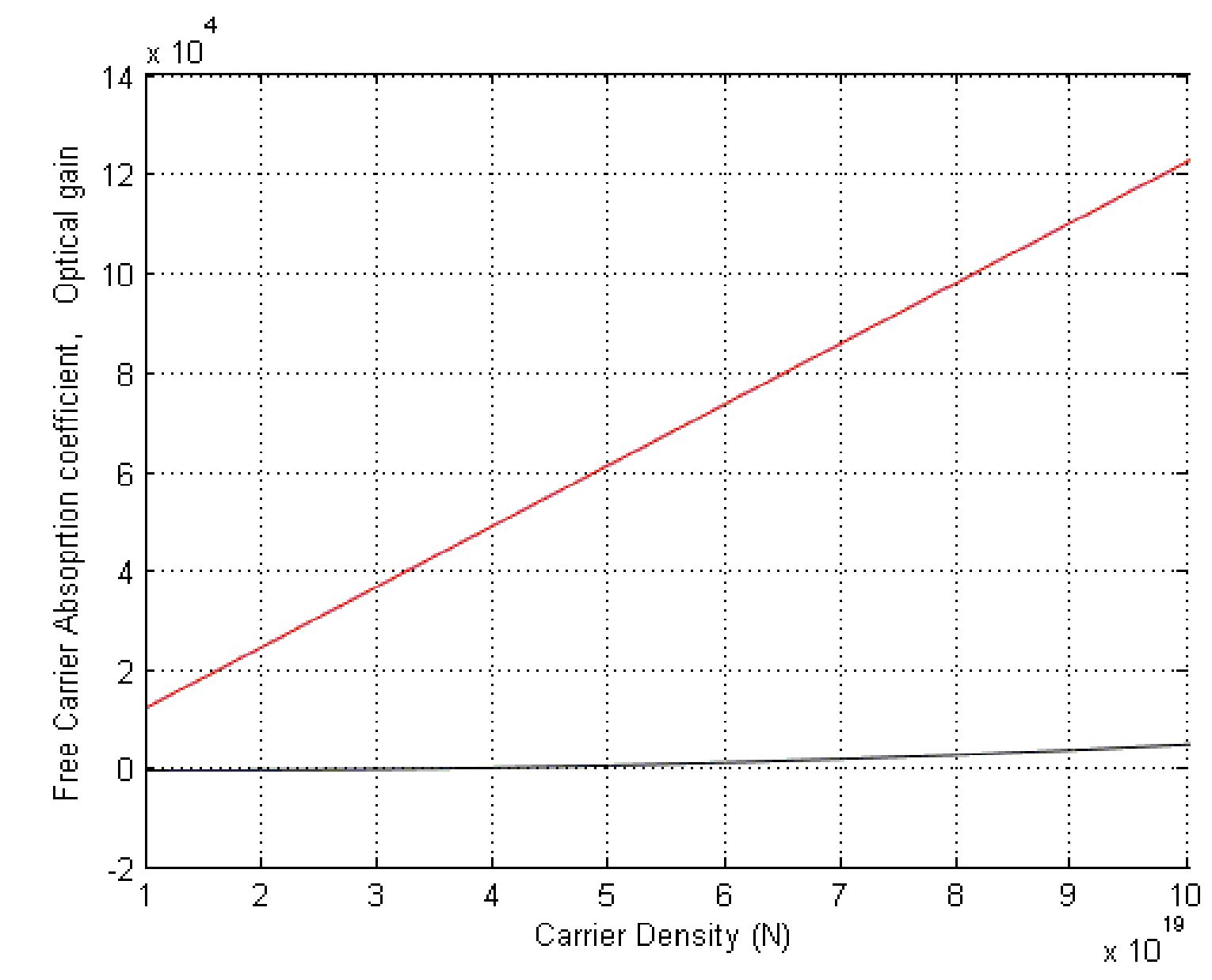
	Below threshold	Above threshold
Carrier density	$N=\frac{\tau_{\mathrm{c,bulk}}}{F_P}R_p$	$N=\sqrt{\frac{K_{p,bulk}}{\tau_{p,bulk}F_{P,bulk}M_{bulk}(\mathrm{n}_{q0}+1+\frac{\tau_qR_p}{K_q})}}\equiv\mathrm{N_{th}}$
Photon density	$\mathrm{N_p}\approx M_{bulk}\tau_{c,bulk}^2\tau_{p,bulk}(n_{q0}+1)R_p^2$	$N_p=F_p\tau_{p,bulk}\left(R_p-F_PM_{bulk}(n_q+1)N_{th}{}^2-F_P\frac{N_{th}}{\tau_{c,bulk}}\right)$
Phonon density	$N_q\approx N_{q0}$	$N_q\approx\mathrm{N}_{q0}+\frac{\tau_qR_p}{K_q}$











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