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CONVERSION OF ENVIRONMENTAL HEAT INTO USABLE ENERGY

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Rezumat. *Prezentăm descoperirea recentă a unui fenomen de conversie a căldurii mediului ambiant în energie de câmp electromagnetic coerent, şi mai departe în energie electrică, pe baza a două dispozitive pe care le-am numit ‚convertor de căldură cuantic' şi ‚sistem de injecţie cuantic'. Un convertor de căldură cuantic se bazează pe cuplarea a două fenomene cunoscute anterior: superradianţa şi efectul Peltier, cuplate printr-un element activ pe care l-am numit ‚transistor superradiant'. Când un curent electric este injectat într-un dispozitiv care conţine un număr suficient de mare de transistoare superradiante, un câmp electromagnetic coerent este emis prin tranziţii cuantice în joncţiunile emitor-bază, pe seama unei absorbții de căldură prin joncţiunile colector-bază. Energia radiată de acest dispozitiv poate fi utilizată direct, în unele aplicaţii, sau convertită în energie electrică prin utilizarea unui sistem de injecţie cuantic.*

Abstract. *We present a recent discovery of a phenomenon of conversion of the environmental heat into coherent electromagnetic energy, and further, into electric energy, on the basis of two semiconductor devices we called ‚quantum heat converter' and, quantum injection system'. A quantum heat converter is based on the coupling of two phenomena, previously known: the superradiance and the Peltier effect, coupled by a active element we called ‚superradiant transistor'. While an electric current is injected in a device containing a sufficiently large number of superradiant transistors, a coherent electromagnetic field is emitted by quantum transitions in the emitter-base junctions, on the a account of heat absorption by the collector-base junctions. The energy radiated by this device can be directly used, in some applications, or converted into electricity by a quantum injection system.*

Keywords: coherent field, correlated transitions, superradiant transistor, quantum heat converter, quantum injection system

1. Introduction

Our civilization is based on large energy consumption, mainly obtained by burning different fuels, chemical, or nuclear. However, these processes producing large chemical, or nuclear wastes, began to become dangerous for our life conditions on this planet.

Consequently, other techniques for the energy production from clean sources as waterfalls, winds, marine tides, or solar radiation, have been developed. However, these technologies are generally based on big installations, with small efficiencies, and critically depending on external conditions, which are not satisfied everywhere on the Earth. A much more accessible energy source is heat, but previously it was believed that its conversion into usable energy is not possible,

due to the second law of thermodynamics [1]. However, approximately in the last half-century, a new remarkable field of science has been developed, we call open quantum physics [2-10]. In this framework, we found that a conversion of the environmental heat into usable energy is possible with a very high efficiency, in the framework of the very well-known technology of the optoelectronic semiconductor devices [11-15].

We showed that principle 2 of thermodynamics does not hold any more in a quantum matter-field system [16]. Such a system, we called superradiant quantum injection dot [17], composed of a two-level system with the density matrix $\rho^S(t)$, and a coupled electromagnetic field with the amplitude $\mathcal{E}(t)$, has an entropy time variation

$$\frac{\mathrm{d}}{\mathrm{d}t}S_{SQD}(t)=\left\{\begin{array}{l}\dfrac{e^2}{2\hbar^2\omega^2K_A^2}\left[\dfrac{\mathrm{d}}{\mathrm{d}t}\left|\mathcal{E}(t)\right|^2+\bar{\gamma}_F\left|\mathcal{E}(t)\right|^2\right]\left[1-\dfrac{\rho_{11}^S(t)}{\rho_{11}^S(t|\infty)}\right] \\ \qquad +2\lambda_{01}\rho_{11}^S(t|\infty)\left[\dfrac{\rho_{11}^S(t)}{\rho_{11}^S(t|\infty)}-\dfrac{\rho_{00}^S(t)}{\rho_{00}^S(t|\infty)}\right]\end{array}\right\} \\ \cdot\left[\ln\frac{\rho_{11}^S(t)}{\rho_{11}^S(t|\infty)}-\ln\frac{\rho_{00}^S(t)}{\rho_{00}^S(t|\infty)}\right], \tag{1}$$

where $\rho_{00}^S(t|\infty)$ and $\rho_{11}^S(t|\infty)$ are the asymptotic values of the occupation probabilities for a field amplitude $\mathcal{E}(t)$, while ω is the frequency of this field, $K_A=\sqrt{\alpha\dfrac{\lambda}{\mathcal{V}_A}}$ is the quantization number of the system with the quantization volume $\mathcal{V}_A$ in a resonant electromagnetic field with a wavelength λ, λ_{01} is the decay rate from the excited state $|1\rangle$ to the ground state $|0\rangle$, $\bar{\gamma}_F$ is the decay rate of the electromagnetic energy, and $e,\hbar,\alpha$ are the usual notations for universal constants. In this expression, we distinguish the positively defined atomic term, proportional to the decay rate λ_{01}, and a term depending on field, which can be negative. Really, when the electromagnetic field increases, the population $\rho_{11}^S(t)$ of the excited states also increases, tending to the asymptotic value $\rho_{11}^S(t|\infty)$ for this field, while the population $\rho_{00}^S(t)$ of the ground state decreases, to the equilibrium value $\rho_{00}^S(t|\infty)$.

With these values, $\rho_{11}^S(t) < \rho_{11}^S(t|\infty)$, $\rho_{00}^S(t) > \rho_{00}^S(t|\infty)$, we get a positive field term in the curly bracket, with the negative logarithmic factor multiplying this bracket.

A microscopic description of this phenomenon has been performed in the framework of a recently developed theory, based on master equations with explicit dissipation coefficients, which depend on the interaction potentials between the system and environmental particles, densities of states, and temperature [18-21]. We showed that this description, with N^2-1 transition operators $c_i^+ c_j$ for a system with N states, $i, j \le N$, is not only more explicit, but also more correct, compared to the most theoretical approaches existing in literature, which take into account only two non-orthogonal operators, coordinate and momentum [22]. In section 2, we present the three master equations of the systems of interest for a semiconductor optoelectronic structure: the activ electrons, the coherent electromagnetic field, and the optical phonons. In section 3, we present the operation of a quantum heat converter. We obtain the output power as a function of the device characteristics and physical constants, and evaluate this power for a realistic system.

2. Quantum master equations for a superradiant transistor

A superradiant transistor is a semiconductor structure, with an array of quantum injection dots, as an emitter-base junction, and a p-i-n deep-level path, as a base-collector junction (Fig. 1). A quantum injection dot is a donor-acceptor pair,

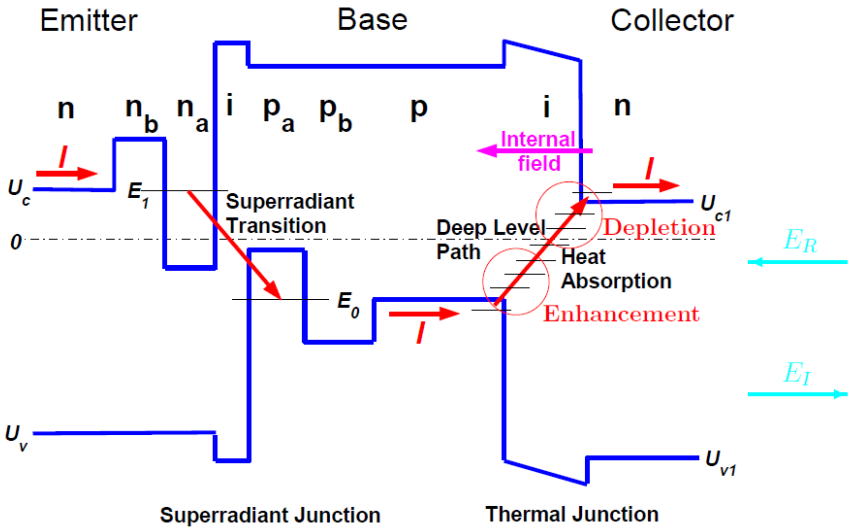

Fig. 1. Superradiant transistor with an n-n_b-n_a-i-p_a-p_b-p superradiant junction and a p-i-n junction with a deep-level path, absorbing heat by Peltier effect.

embedded in two n_a and p_a thin layers, of lower band gap, with an i-layer of a higher band gap between these layers. The quantum dot density $N_e\left[m^{-2}\right]$, the thicknesses $x_0 - x_1$ and $x_4 - x_2$ of the two layers n_a and p_a, the thickness $x_2 - x_0$ of the i-layer, and the barriers U_3 and U_4 with the thicknesses $x_1 - x_3$ and $x_5 - x_4$, between the conduction regions n and p with the conduction and valence band margins U_c and U_v (**Fig. 2**), are chosen for quantum dot eigenenergies

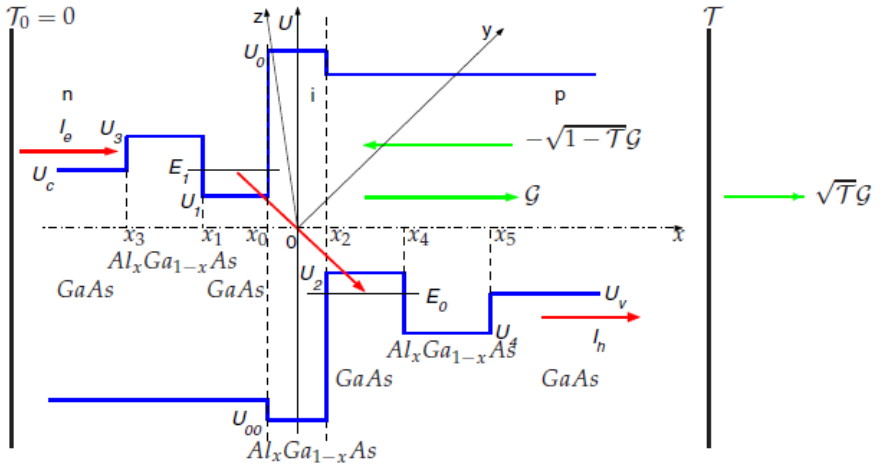

Fig. 2. Quantum injection dot with the energy levels E_0 and E_1, coupled to a coherent electromagnetic field $\mathcal{E} = \mathcal{F} + \mathrm{i}\,\mathcal{G} = \mathrm{i}\,\mathcal{G}$, in a cavity with mirror transmission coefficients $\mathcal{T}_0 = 0$ and $\mathcal{T}$, while an electron current $I = I_e = I_h$ is injected in this quantum dot.

$E_1 = U_c, E_0 = U_v$. The two potential barriers, which separate the quantum dot levels E_1 and E_0 from the high density levels of the conduction regions n and p, diminish the dissipative coupling of the active quantum dot electrons to the conduction electrons and holes. Of course, the dimensions of the separation barriers are chosen for a sufficient high penetrability, to provide the necessary electron flow for the device operation. When a sufficiently high current is injected in the device, a coherent electromagnetic field of an amplitude $\mathcal{E}$ is generated, by quantum transitions from the excited state $|1\rangle$ with the energy E_1, to the ground state $|0\rangle$ with the energy E_0. When these electrons cross the base-collector junction, the lower states of the deep level path are enhanced, while the higher states of this path are depleted, which means a temperature decrease of this junction. This leads to heat absorption in this junction, tending to remake the electron distribution for the environmental temperature T.

The field amplitude $\mathcal{E}$ is determined by the coupling of this field to the quantum transitions $|1\rangle \rightarrow |0\rangle$, and other couplings in this matter-field system:

1. The dissipative couplings of the active electrons with the crystal lattice vibrations, the conduction electrons and holes, and the free electromagnetic field existing at a certain temperature T;
2. The coupling of the electromagnetic field with the optical vibrations of the crystal lattice, and the dissipative couplings with the conduction electrons and holes;
3. The dissipative couplings of the optical vibrations of the crystal lattice with the valence electrons.

Consequently, we describe this physical system by three master equations [10]:

1. Master equation for a system of Fermions interacting with an electromagnetic field, with dissipative coefficients for couplings to other Fermions, Bosons, and a free electromagnetic field;
2. Master equation for an electromagnetic field mode interacting with a system of active Fermions and the optical vibrations of a crystal lattice, with dissipative coefficients for couplings to an environment of other Fermions;
3. Master equation for the optical vibrations of a crystal lattice excited by an electromagnetic field, with dissipative coefficients for the coupling to the valence electrons.

We consider a system of Fermions described by the creation-annihilation operators $c_i^+ \text{-} c_i$, and an energy spectrum ε_i in a potential well situated at a coordinate x of a Fabry-Perot cavity, with the resonant electromagnetic field modes of the cavity $a_+^+ \text{-} a_+$ for the forward wave, and $a_-^+ \text{-} a_-$ for the backward wave. Here, we take into account dimensions of this well much smaller than the electromagnetic field wavelength. This system is described by a Hamiltonian

$$H = H_0 + V, \tag{2}$$

where

$$H_0 = \sum_i \varepsilon_i c_i^+ c_i \tag{3}$$

is the Hamiltonian of the system of Fermions, and

$$V = \mathrm{i}\sum_{j>i} \hbar\omega_{ji} \vec{K}_A \vec{r}_{ij} \left[c_j^+ c_i \left(a_+ e^{\mathrm{i}kx} + a_- e^{-\mathrm{i}kx} \right) - c_i^+ c_j \left(a_+^+ e^{-\mathrm{i}kx} + a_-^+ e^{\mathrm{i}kx} \right) \right] \tag{4}$$

is the interaction potential of this system in electromagnetic field, with the transition frequencies $\omega_{ji}=\dfrac{\varepsilon_j-\varepsilon_i}{\hbar}$ and the dipole moments $\vec{r}_{ij}=\langle i|\vec{r}|j\rangle$. The dynamics of such a system in a dissipative system of Y^F Fermions, with a density of states $g^F(\varepsilon_\alpha)$, a mean number $f^F(\varepsilon_\alpha)$ of Fermions on these states, and a potential V^F, a system of Bosons, with a density of states $g^B(\varepsilon_\alpha)$, a mean number $f^B(\varepsilon_\alpha)$ on these states, and a potential V^B, and a free electromagnetic field at a temperature T, is described by the quantum master equation [10,15,21]:

$$\begin{aligned}\frac{\mathrm{d}}{\mathrm{d}t}\rho(t)=&-\frac{\mathrm{i}}{\hbar}\left[H,\rho(t)\right]-\mathrm{i}\sum_{ij}\zeta_{ij}\left[c_i^+c_j,\rho(t)\right]\\&+\sum_{ij}\lambda_{ij}\left(\left[c_i^+c_j\rho(t),c_j^+c_i\right]+\left[c_i^+c_j,\rho(t)c_j^+c_i\right]\right)\\&+\sum_{ijkl}\zeta_{ij}\zeta_{kl}\int_{t-\tau}^{t}\left[c_i^+c_j,e^{-\mathrm{i}\left[\varphi(t')+\frac{1}{\hbar}H_0(t-t')\right]}\left[c_k^+c_l,\rho(t)\right]e^{\mathrm{i}\left[\varphi(t')+\frac{1}{\hbar}H_0(t-t')\right]}\right]\mathrm{d}t'.\end{aligned}\tag{5}$$

This equation depends on the dissipative potential fluctuations ζ_{ij}, of the amplitude mean-value

$$\bar{\zeta}_{ij}=\frac{1}{\hbar}\sqrt{\frac{1}{Y^F}\int_{(\alpha)}\left\langle\alpha i\left|\left(V^F\right)^2\right|\alpha j\right\rangle f^F(\varepsilon_\alpha)g^F(\varepsilon_\alpha)\mathrm{d}\varepsilon_\alpha},\tag{6}$$

the memory time τ, and the random phases $\phi(t')$, of these fluctuations, and the dissipative coefficients

$$\lambda_{ij}=\lambda_{ij}^F+\lambda_{ij}^B+\gamma.\tag{7}$$

For $i<j$ and transition energies much larger than the thermal energy, $\varepsilon_{ji}>>T$, the terms of these coefficients are of the form

$$\begin{aligned}\lambda_{ij}^F&=\frac{\pi}{\hbar}\left|\langle\alpha i|V^F|\beta j\rangle\right|^2\left[1-f^F(\varepsilon_{ji})\right]g^F(\varepsilon_{ji})\\\lambda_{ji}^F&=\frac{\pi}{\hbar}\left|\langle\alpha i|V^F|\beta j\rangle\right|^2 f^F(\varepsilon_{ji})g^F(\varepsilon_{ji}),\end{aligned}\tag{8}$$

for the coupling with the environmental Fermions,

$$\lambda_{ij}^{B} = \frac{\pi}{\hbar}\left|\langle \alpha i|V^{B}|\beta j\rangle\right|^{2}\left[1+ f^{B}\left(\varepsilon_{ji}\right)\right]g^{B}\left(\varepsilon_{ji}\right)$$
$$\lambda_{ji}^{B} = \frac{\pi}{\hbar}\left|\langle \alpha i|V^{B}|\beta j\rangle\right|^{2} f^{B}\left(\varepsilon_{ji}\right)g^{B}\left(\varepsilon_{ji}\right), \quad (9)$$

for the coupling with the environmental Bosons, and

$$\gamma_{ij} = \frac{2\alpha}{c^{2}\hbar^{3}}\left|\vec{r}_{ij}\right|^{2}\varepsilon_{ji}^{3}\left(1+\frac{1}{e^{\varepsilon_{ji}/T}-1}\right), \quad (10)$$

for the coupling with the free electromagnetic field at a temperature T. These coefficients describe a resonant dissipation, when a transition of a Fermion of the system of interest is correlated to a transition of an environmental particle, with a certain probability (**Fig. 3**).

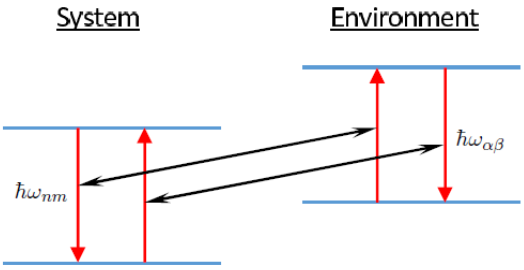

Fig. 3. Resonant dissipation.

These probabilities correspond to the detailed balance principle [22]. For a system of active electrons in a semiconductor structure, the dissipation coefficients λ_{ij}^{F} and λ_{ji}^{F} of the coupling with a conduction electron situated at a distance r in a conduction region, is obtained with the Coulomb potential of interaction

$$V^{F}(r) = \frac{\alpha\hbar c}{r}c_{\alpha}^{+}c_{i}^{+}c_{j}c_{\beta}. \quad (11)$$

For a two-level quantum dot in a crystal lattice, which is of interest for our application, the dissipation coefficients of the coupling to the vibrational modes of this lattice are of the form [15]:

$$\lambda_{01}^{P} = \sum_{\alpha}\frac{M^{2}c^{4}\varepsilon_{10}^{5}}{\pi\hbar^{6}c^{4}v^{3}D}\cdot\frac{\left(\vec{r}_{01}\vec{1}_{\alpha}\right)^{2}}{1-e^{-\varepsilon_{10}/T}} \quad (12)$$

$$\lambda_{10}^{P}=\sum_{\alpha}\frac{M^{2}c^{4}\varepsilon_{10}^{5}}{\pi\hbar^{6}c^{4}v^{3}D}\cdot\frac{\left(\vec{r}_{01}\vec{1}_{\alpha}\right)^{2}}{e^{\varepsilon_{10}/T}-1}, \tag{13}$$

where M is the electron mass, $a_{\nu\alpha}^{+}$ - $a_{\nu\alpha}$ are creation-annihilation operators of phonons of frequency ν and polarization $\vec{1}_{\alpha}$, D is the crystal density, and

$$v=\sqrt{\frac{E}{D}} \tag{14}$$

is the sound velocity in a crystal with a Young elasticity coefficient E. In such a dissipation process, an electron decay/excitation with an energy ε_{10} is correlated to a phonon creation/annihilation of the same energy, $\hbar\omega_{\nu}=\varepsilon_{10}$.

From the master equation (5), we derive equations of the density matrix elements, for a two-level system with a transition energy $\varepsilon_{10}=\hbar\omega_{0}$, which depend on a quasi-resonant electromagnetic field of amplitude $\mathcal{E}(t)$ and frequency $\omega\approx\omega_{0}$,

$$\vec{E}(t)=\frac{1}{2}\left[\mathcal{E}(t)e^{-\mathrm{i}\omega t}+\mathcal{E}^{*}(t)e^{\mathrm{i}\omega t}\right]\vec{1}_{E}. \tag{15}$$

For the polarization amplitude $S(t)$,

$$\rho_{10}(t)=\frac{1}{2}S(t)e^{-\mathrm{i}\omega t}, \tag{16}$$

and the population difference

$$\begin{aligned} w(t)&=\rho_{11}(t)-\rho_{00}(t),\\ 1&=\rho_{11}(t)-\rho_{00}(t), \end{aligned} \tag{17}$$

we obtain the polarization-population equations

$$\begin{aligned} \frac{\mathrm{d}}{\mathrm{d}t}S(t)&=-\gamma_{\perp}(1-\mathrm{i}\delta\omega)S(t)+\mathrm{i}g\mathcal{E}(t)w(t)+\gamma_{n}^{2}\int_{t-\tau}^{t}S(t')e^{\mathrm{i}(\omega-\omega_{0})(t-t')}\mathrm{d}t'\\ \frac{\mathrm{d}}{\mathrm{d}t}w(t)&=-\gamma_{\parallel}\left[w(t)-w_{T}\right]-\mathrm{i}\frac{g}{2}\left[\mathcal{E}(t)S^{*}(t)-\mathcal{E}^{*}(t)S(t)\right], \end{aligned} \tag{18}$$

which depend on the coupling coefficient $g=\frac{e}{\hbar}\vec{r}_{01}\vec{1}_{E}$, the dephasing rate $\gamma_{\perp}=\lambda_{01}+\lambda_{10}+\lambda_{00}+\lambda_{11}$, the decay rate $\gamma_{\parallel}=2(\lambda_{01}+\lambda_{10})$, the equilibrium

population $w_T = -\frac{\lambda_{01}-\lambda_{10}}{\lambda_{01}+\lambda_{10}}$ at a temperature T, the non-Markovian fluctuation coefficient $\gamma_n = \zeta_{11}-\zeta_{00}$, and the relative atomic detuning $\delta\omega = \frac{\omega-\omega_0-\gamma_n}{\gamma_\perp}$. The superradiant field generated by the quantum transitions of this system, which propagates through the semiconductor, is highly influenced by the uncanceled charge of valence electron distribution over the ion distribution of this material, which leads to an important variation of the field propagation velocity, according to a refractive index $\eta >> 1$ (**Fig. 4**).

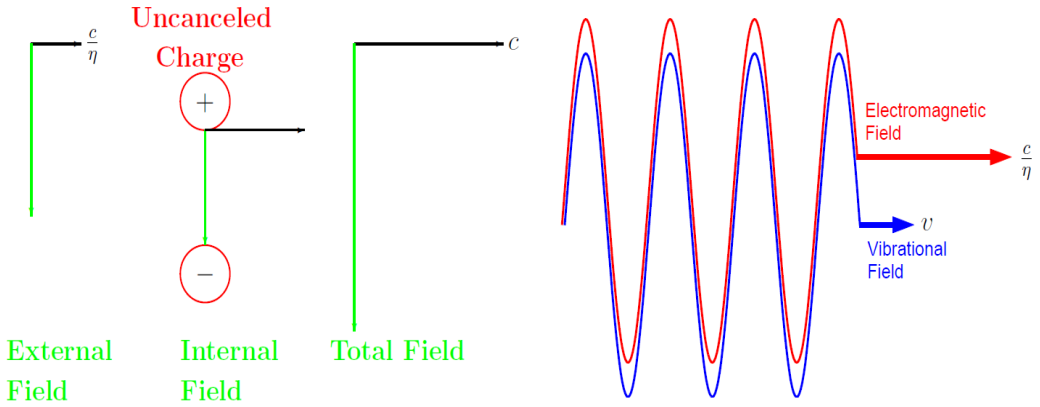

Fig. 4. An external electromagnetic field exciting an internal field of the uncanceled charge in the crystal, and an optical vibration of this crystal, which propagates with the sound velocity v.

Really, the Hamiltonian

$$H = \frac{\left(\vec{p}+e\vec{A}\right)^2}{2M} - eU\left(\vec{r}\right) \tag{19}$$

of an electron in a potential $U(\vec{r})$, and an electromagnetic field of vector potential $\vec{A}(x) = \frac{\hbar\vec{K}}{e}\left(a_+e^{ikx} + a_+^+e^{-ikx} + a_-e^{-ikx} + a_-^+e^{ikx}\right)$, with $\vec{K} = \vec{1}_E\sqrt{\alpha\frac{\lambda}{\mathcal{V}}}$ as the field quantization vector, includes a field term $W = \frac{e^2}{2M}\vec{A}^2 = \frac{\hbar^2\vec{K}^2}{M}\left(a_+^+a_+ + a_-^+a_- + 1\right)$. This means an additional field energy $\overline{W} = 4Nf_u\frac{\hbar^2K^2}{M}$, in the field quantization volume $\mathcal{V}$ with N atoms and an uncanceled charge ratio f_u, besides the photon energy $\hbar\omega$, *i.e.* a refractive index

$$\eta = 1 + \frac{\bar{W}}{\hbar\omega} = \frac{1}{2}\left(1 + \sqrt{1 + 32\pi\alpha f_u \frac{\hbar c D}{M M_A \omega^2}}\right), \tag{20}$$

where M_A is the atomic mass.

We obtain master equations for the electromagnetic field propagating forward,

$$\begin{aligned}\frac{\mathrm{d}}{\mathrm{d}t}\rho_+^F(x,t) &= -\mathrm{i}\omega\left[a_+^+ a_+, \rho_+^F(x,t)\right] \\ &+ \sum_{j>i}\omega_{ji}\vec{K}_A\vec{r}_{ij}\left[\left\langle c_j^+ c_i\right\rangle a_+ e^{\mathrm{i}kx} - \left\langle c_i^+ c_j\right\rangle a_+^+ e^{-\mathrm{i}kx}, \rho_+^F(x,t)\right] \\ &+ \mathrm{i}\frac{\omega}{2\omega_\nu} K\nu\left[\left\langle a_{\nu+}^+\right\rangle a_+ e^{\mathrm{i}(\omega-\omega_\nu)t} + \left\langle a_{\nu+}\right\rangle a_+^+ e^{-\mathrm{i}(\omega-\omega_\nu)t}, \rho_+^F(x,t)\right] \\ &+ \Lambda_x \int_0^x \left\{\left[a_+ \rho_+^F(x',t'), a_+^+\right] + \left[a_+, \rho_+^F(x',t') a_+^+\right]\right\} e^{-\mathrm{i}k(x-x')}\mathrm{d}x',\end{aligned} \tag{21}$$

and the electromagnetic field propagating backward,

$$\begin{aligned}\frac{\mathrm{d}}{\mathrm{d}t}\rho_-^F(x,t) &= -\mathrm{i}\omega\left[a_-^+ a_-, \rho_-^F(x,t)\right] \\ &+ \sum_{j>i}\omega_{ji}\vec{K}_A\vec{r}_{ij}\left[\left\langle c_j^+ c_i\right\rangle a_- e^{-\mathrm{i}kx} - \left\langle c_i^+ c_j\right\rangle a_-^+ e^{\mathrm{i}kx}, \rho_-^F(x,t)\right] \\ &+ \mathrm{i}\frac{\omega}{2\omega_\nu} K\nu\left[\left\langle a_{\nu-}^+\right\rangle a_- e^{\mathrm{i}(\omega-\omega_\nu)t} + \left\langle a_{\nu-}\right\rangle a_-^+ e^{-\mathrm{i}(\omega-\omega_\nu)t}, \rho_-^F(x,t)\right] \\ &+ \Lambda_x \int_x^{L_D} \left\{\left[a_- \rho_-^F(x',t'), a_-^+\right] + \left[a_-, \rho_-^F(x',t') a_-^+\right]\right\} e^{-\mathrm{i}k(x'-x)}\mathrm{d}x',\end{aligned} \tag{22}$$

with a wave number $k = \dfrac{\eta\omega}{c}$.

These equations are coupled with master equations for the optical vibrations propagating forward,

$$\begin{aligned}\frac{\mathrm{d}}{\mathrm{d}t}\rho_+^P(x,t) &= -\mathrm{i}\omega_\nu\left[a_{\nu+}^+ a_{\nu+}, \rho_+^P(x,t)\right] \\ &+ \mathrm{i}\frac{\omega_\nu^2}{2K\nu}\left[\left\langle a_+^+\right\rangle a_{\nu+} e^{-\mathrm{i}(\omega-\omega_\nu)t} + \left\langle a_+\right\rangle a_{\nu+}^+ e^{\mathrm{i}(\omega-\omega_\nu)t}, \rho_+^P(x,t)\right] \\ &+ \Lambda_x^P \int_0^x \left\{\left[a_{\nu+} \rho_+^P(x',t'), a_{\nu+}^+\right] + \left[a_{\nu+}, \rho_+^P(x',t') a_{\nu+}^+\right]\right\} e^{-\mathrm{i}k_\nu(x-x')}\mathrm{d}x',\end{aligned} \tag{23}$$

and backward,

$$\frac{\mathrm{d}}{\mathrm{d}t}\rho_{-}^{P}\left(x,t\right)=-\mathrm{i}\omega_{\nu}\left[a_{\nu-}^{+}a_{\nu-},\rho_{-}^{P}\left(x,t\right)\right]$$
$$+\mathrm{i}\frac{\omega_{\nu}^{2}}{2Kv}\left[\left\langle a_{-}^{+}\right\rangle a_{\nu-}e^{-\mathrm{i}(\omega-\omega_{\nu})t}+\left\langle a_{-}\right\rangle a_{\nu-}^{+}e^{\mathrm{i}(\omega-\omega_{\nu})t},\rho_{-}^{P}\left(x,t\right)\right] \tag{24}$$
$$+\Lambda_{x}^{P}\int_{x}^{L_{D}}\left\{\left[a_{\nu-}\rho_{-}^{P}\left(x',t'\right),a_{\nu-}^{+}\right]+\left[a_{\nu-},\rho_{-}^{P}\left(x',t'\right)a_{\nu+}^{+}\right]\right\}e^{-\mathrm{i}k_{\nu}(x'-x)}\mathrm{d}x',$$

generated by the electromagnetic field with the same wavelength, or wave vector $k_{\nu}=k$ (**Fig. 4**), which means a frequency

$$\omega_{\nu}=\omega\frac{\eta\nu}{c}=\omega\frac{\eta}{c}\sqrt{\frac{E}{D}}. \tag{25}$$

The master equations (21)-(22) of an electromagnetic field in a quantization volume $\mathcal{V}=1_{L}^{3}$, describe the couplings of this field to the active electrons with the transition operators $c_{j}^{+}c_{i}$, the optical vibrations with the creation-annihilation operators $a_{\nu+}^{+}$ - $a_{\nu+}$ and $a_{\nu-}^{+}$ - $a_{\nu-}$, and the quasi-free electrons/holes encountered in the conduction regions, by propagation between the two surfaces of the device, $x'=0$ and $x'=L_{D}$, with the dissipation coefficient

$$\Lambda_{x}=\frac{4\alpha}{\hbar}\sqrt{2Mc^{2}\hbar\omega}\,\frac{L_{D}}{1_{L}^{2}}. \tag{26}$$

The master equations (23)-(24), of the optical vibrations of a crystal lattice with a lattice constant a and an uncanceled charge ratio f_{u}, describe the coupling to the electromagnetic field exciting these vibrations, with the creation-annihilation operators a_{+}^{+} - a_{+} and a_{-}^{+} - a_{-}, and the valence electrons excited by these vibrations to free states at a temperature T, with the dissipation coefficient

$$\Lambda_{x}^{P}=f_{u}^{2}a^{2}1_{L}L_{D}c\frac{\left(Mc^{2}\right)^{5}\left(\hbar\omega_{\nu}\right)^{3}T^{2}}{4\pi^{3}\left(\hbar c\right)^{9}Dc^{2}}e^{(U_{v}+\hbar\omega_{\nu})/T}. \tag{27}$$

From the master equations (21)-(22) of the electromagnetic field, and (23)-(24) of the optical vibrations, for the mean values of the field

$$\left\langle a_{+}\right\rangle=\mathrm{Tr}\left\{a_{+}\rho_{+}^{F}\left(x,t\right)\right\}=\mathcal{A}_{+}\left(x,t\right)e^{-\mathrm{i}\omega t} \tag{28}$$

$$\left\langle a_{-}\right\rangle = \mathrm{Tr}\left\{a_{-}\rho_{-}^{F}\left(x,t\right)\right\} = \mathcal{A}_{-}\left(x,t\right)e^{-\mathrm{i}\omega t}, \tag{29}$$

and the matrix elements $\rho_{10}(x,t) = \frac{1}{2}\left[S_{+}(x,t)e^{\mathrm{i}kx} + S_{-}(x,t)e^{-\mathrm{i}kx}\right]e^{-\mathrm{i}\omega t}$, we obtain the amplitude equations

$$\begin{aligned}\frac{\mathrm{d}^2}{\mathrm{d}t^2}\mathcal{A}_{+}\left(x,t\right) + \frac{\Lambda_x + \Lambda_x^P}{2k}\left(1-\mathrm{i}\sqrt{3}\right)\frac{\mathrm{d}}{\mathrm{d}t}\mathcal{A}_{+}\left(x,t\right) + \Omega_R^2\mathcal{A}_{+}\left(x,t\right) \\ = -\frac{1}{2}\omega_0\vec{K}_A\vec{r}_{01}\frac{\mathrm{d}}{\mathrm{d}t}S_{+}\left(x,t\right)\end{aligned} \tag{30}$$

$$\begin{aligned}\frac{\mathrm{d}^2}{\mathrm{d}t^2}\mathcal{A}_{-}\left(x,t\right) + \frac{\Lambda_x + \Lambda_x^P}{2k}\left(1-\mathrm{i}\sqrt{3}\right)\frac{\mathrm{d}}{\mathrm{d}t}\mathcal{A}_{-}\left(x,t\right) + \Omega_R^2\mathcal{A}_{-}\left(x,t\right) \\ = -\frac{1}{2}\omega_0\vec{K}_A\vec{r}_{01}\frac{\mathrm{d}}{\mathrm{d}t}S_{-}\left(x,t\right),\end{aligned} \tag{31}$$

which describe a Raman frequency shift $\Omega_R = \frac{\sqrt{\omega\omega_\nu}}{2}$. From these equations with (20) and (25)-(27), and the polarization-population equations (18) with (6)-(8) and (10)-(14), we obtain an analytical description of a superradiant semiconductor structure, depending on the crystal atomic mass M_A, the crystal density D, the uncanceled charge ratio f_u, the quasi-resonant quantum dot frequency $\omega_0 \approx \omega$, the conduction electron/hole density $g^F(\hbar\omega_0)$, the donor and acceptor concentrations N_D and N_A of the conduction regions which determine the potentials U_c and U_v, the Coulomb potential V^F of the conduction electrons and holes in the field of a quantum dot, the elasticity coefficient E, the quantum dot transition dipole moment $\vec{r}_{01}$, and the thickness L_D of the active structure.

3. Quantum heat converter

A quantum heat converter is a device composed of a packet of superradiant transistors in a Fabry-Perot cavity with a total reflection mirror, $\mathcal{T}_0 = 0$, and an output mirror with a transmission coefficient $\mathcal{T}$, in intimate contact with a heat absorbent (**Fig. 5**) [10], [12-17]. The quantum dot arrays of these transistors are situated in the antinodes of a quasi-resonant electromagnetic mode of the cavity, while the heat absorbing junctions are placed in nodes. An electromagnetic field flow Φ is generated by a strong electron-field coupling in antinodes, while the absorption of this field by the weak electron-field coupling in nodes is negligible. Two versions of this device are conceivable: (1) a longitudinal device, with the two mirrors on the two surfaces of the semiconductor chip, and (2) a transversal device, with the two mirrors on two lateral surfaces of the cheap.

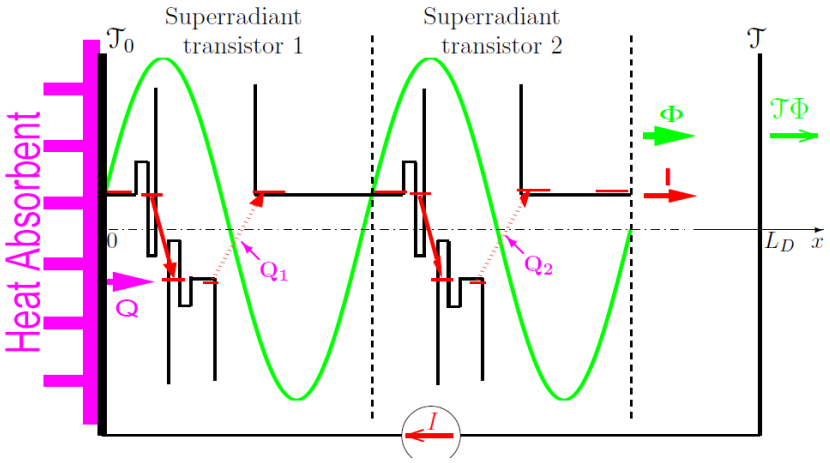

Fig. 5. Quantum heat converter, as a packet of superradiant transistors in a Fabry-Perot cavity, with the superradiant emitter-base junctions in the antinodes of a quasi-resonant electromagnetic mode of the cavity, and the heat absorbing base-collector junctions in nodes.

With a chip of active area A_D and thickness L_D, including $\bar{N}_t$ superradiant transistors with a quantum dot density N_e, we obtain the energy flows for a longitudinal device,

$$\Phi_L = K_R \frac{\bar{N}_t}{\left(2-\mathcal{T}\right)\left(1+2\eta\frac{1_L\bar{\gamma}_F}{c\mathcal{T}}\right)}\frac{\hbar\omega}{e}\left(I-I_{0L}\right), \tag{32}$$

and a transversal one,

$$\Phi_T = K_R \frac{\bar{N}_t}{\left(2-\mathcal{T}\right)\left(1+2\eta\frac{1_L\bar{\gamma}_F}{c\mathcal{T}}\frac{\sqrt{A_D}}{L_D}\right)}\frac{\hbar\omega}{e}\left(I-I_{0T}\right), \tag{33}$$

depending on threshold currents

$$I_{0L} = eN_eA_D\gamma_\parallel\frac{1}{2}\left[-w_T+\frac{\gamma_\perp}{4\pi\alpha\omega\bar{N}_tN_e\left(\vec{r}_{01}\vec{1}_E\right)^2}\left(\mathcal{T}+2\eta\frac{1_L\bar{\gamma}_F}{c}\right)\right] \tag{34}$$

$$I_{0T} = eN_eA_D\gamma_\parallel\frac{1}{2}\left[-w_T+\frac{\gamma_\perp}{4\pi\alpha\omega\bar{N}_tN_e\left(\vec{r}_{01}\vec{1}_E\right)^2}\left(\mathcal{T}\frac{L_D}{\sqrt{A_D}}+2\eta\frac{1_L\bar{\gamma}_F}{c}\right)\right], \tag{35}$$

and a coefficient K_R for to the Raman effect, which, for a sufficiently low dephasing rate $\gamma_\perp << \Omega_R$, is $K_R\left(\mathcal{T}\right)\approx 1$.

We notice that the current I injected in the device must be lower than the maximum value $I_M = eN_e A_D \gamma_{||}(-w_T)$, otherwise the quantum dot neutrality is no more spared. Thus, we obtain an operation condition for the thresholds of the population inversions in the expressions (34) and (35) of the threshold currents:

$$w_{IL} = \frac{\gamma_\perp}{4\pi\alpha\omega\bar{N}_t N_e \left(\vec{r}_{01}\vec{1}_E\right)^2}\left(\mathcal{T} + 2\eta\frac{1_L\bar{\gamma}_F}{c}\right) < -w_T \approx 1, \tag{36}$$

$$w_{IT} = \frac{\gamma_\perp}{4\pi\alpha\omega\bar{N}_t N_e \left(\vec{r}_{01}\vec{1}_E\right)^2}\left(\mathcal{T}\frac{L_D}{\sqrt{A_D}} + 2\eta\frac{1_L\bar{\gamma}_F}{c}\right) < -w_T \approx 1, \tag{37}$$

i.e. for the quantum dot density N_e, the number of superradiant transistors $\bar{N}_t$, the dipole moment $\vec{r}_{01}$, the dephasing rate $\gamma_\perp$, and the decay rate of the field $\bar{\gamma}_F$.

For reasonable values of a $GaAs\text{-}Al_xGa_{1-x}As$ semiconductor structure, with an active zone area $A_D = 4cm^2$, and thickness $L_D = 2mm$, donor and acceptor concentrations $N_D = N_A = 3.16\times10^{16}cm^{-3}$, which mean a density of superradiant dots $N_e = 1.476\,\mathrm{m}^{-2}$ and a transition frequency $\hbar\omega_0 = 0.186eV$, *i. e.* a field frequency $\omega \approx \omega_0 = 2.82\times10^{14}s^{-1}$, which, for the refractive index $\eta = 3.3$, means $\bar{N}_t = 1000$ superradiant transistors in this structure, a transition dipole moment $|\vec{r}_{01}| = 5\times10^{-4}nm$, a dephasing rate $\gamma_\perp = 1.9\times10^7\,\mathrm{s}^{-1}$, and a field decay rate $\bar{\gamma}_F = 4.2\times10^6\,s^{-1}$, which means a transmission coefficient of the output mirror $\mathcal{T} = 0.210$, we obtain the population inversion threshold

$$\begin{aligned} w_{IL} &= \frac{1.9\times10^7\,\mathrm{s}^{-1}\left(0.21 + 2\cdot3.3\dfrac{1\mathrm{m}\cdot4.2\times10^6\,\mathrm{s}^{-1}}{3\times10^8\,\mathrm{m\,s}^{-1}}\right)}{\dfrac{4\pi}{137}\cdot2.82\times10^{14}s^{-1}\cdot10^3\cdot1.476\times10^{16}\left(10^9\,nm\right)^{-2}\cdot25\times10^{-8}\,nm^2} \\ &= \frac{1.9\times10^7\,\mathrm{s}^{-1}\left(0.21+0.0924\right)}{9.5448\times10^7\,\mathrm{s}^{-1}} = 0.06 < 1. \end{aligned} \tag{38}$$

With a decay rate $\gamma_{||} = 2\gamma_\perp$, from (34) with (36) and (38), we obtain the threshold current $I_{0L} = 1.6\times10^{-19}C\cdot1.476\times10^{16}\,\mathrm{m}^{-2}\cdot4\left(0.01\mathrm{m}\right)^2\cdot1.9\times10^7\mathrm{s}^{-1}\cdot1.06 = 19\,\mathrm{A}$. For a current $I = 34\,\mathrm{A} < I_M = 35.896\,\mathrm{A}$, injected in this chip with an electric resistance

$$R = \frac{0.2\ \text{cm}/\left(4\ \text{cm}^2\right)}{1.6\times10^{-19}\text{C}\cdot 3.16\times10^{16}\text{cm}^{-3}}\left(\frac{3}{4\cdot 8000}+\frac{1}{4\cdot 400}\right)\frac{1}{\text{cm}^2\text{V}^{-1}\text{s}^{-1}} = 7.1\ \text{m}\Omega, \quad (39)$$

from (32) we obtain an electromagnetic power

$$\Phi_L = \frac{1\cdot 1000\cdot 0.186\ V\left(34-19\right)A}{\left(2-0.21\right)\left(1+2\cdot 3.3\dfrac{1\text{m}\cdot 4.2\times10^{6}\,s^{-1}}{3\times10^{8}\,\text{m}\,s^{-1}\cdot 0.21}\right)} = 1.082\ \text{kW}, \quad (39)$$

much larger than the electric power $P_E = RI^2 = 8.2\ \text{W}$, which is necessary for this current injection.

Conclusions

We proposed a new technological development for the energy production, by heat absorption from the environment. In this framework, high efficiency devices are feasible: for instance, we obtained $1\ \text{kW}$ from a superradiant chip with an area of $4\ \text{cm}^2$ and a thickness of $2\ \text{mm}$. A microscopic theory is available for a complete analytical description. In this framework, the essential characteristics of the device are readily understandable from physical reasons.

Thus, we found that the superradiant power is proportional to the transition energy of the active quantum dots, the electric current injected over a threshold value, and the number of superradiant transistors, and is inverse proportional to a term describing the absorption of the field in its propagation through the cavity, and a term depending on the transparency of the output mirror.

This transparency is determined from the condition of stationary waves propagation in the cavity, depending on the absorption coefficient of these waves. The threshold current is proportional to the quantum dot density, the area of the active zone, and the decay rate of the active electrons.

The quantum dot density is determined from the transition energy condition, for the electron injection from the n-zone of the emitter to the *p*-zone of the base. The threshold current essentially depends on the population inversion, which is proportional to the dephasing rate and the sum of the output mirror transparency with the field absorption term, and inverse proportional to the transition frequency, the number of superradiant transistors, the quantum dot density, and the square of the transition dipole moment.

These characteristics are obtained as explicit functions of the crystal properties, and device parameters.

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