On the possibility of producing a coherent scintillator

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It is shown that a coherent scintillator can, in principle, be produced in an external resonance electromagnetic field.

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1. As shown in Refs. 1 and 2, the action of an electromagnetic field on a material of relatively low density may produce conditions for coherent de-excitation of excited atoms of the material by a fast particle. In view of this, it is of interest to determine whether a coherent scintillator based on impurity atoms can be produced in a dense material in which the impurity atoms would have a coherent emission.

2. We shall analyze, for example, a material with impurity atoms (molecules) which are chosen in such a way that the excitation energy of the first excited level of the base material coincides with the energy E_3 of the third excited level of an impurity atom (molecule). We shall assume that the transitions between the levels E_3 and E_1, E_3 and E_0, E_2 and E_1, and E_2 and E_0 ($E_3 > E_2 > E_1 > E_0$) are resolved in the impurity atom, but the $3 \to 2$ and $1 \to 0$ transitions are forbidden.

To ensure, just as in Ref. 2, that the different impurity atoms will produce a coherent emission, we apply an additional electromagnetic field to the material in the form of a sum of two plane waves

$$\mathbf{E}(\mathbf{R}, t) = \mathbf{E}_0 \{\exp(i\mathbf{k}_0\mathbf{R} - \omega_0 t) + \text{c.c.}\} + \mathbf{E}_1 \{\exp(i\mathbf{k}_1\mathbf{R} - \omega_1 t) + \text{c.c.}\} \tag{2.1}$$

after choosing the frequencies in the form $\omega_0 = \omega_{21} \equiv E_2 - E_1$; $\omega_1 = \omega_{31} \equiv E_3 - E_1$.

Assuming that the excitation of the atoms of a material is determined by the field of a particle

$$\mathbf{E}_p(\mathbf{R}, t) = \int d^3q \mathbf{E}_p(\mathbf{q}) \exp\{i\mathbf{q}\mathbf{R} - i\mathbf{q}\mathbf{v}t\}; \quad \mathbf{E}_p(\mathbf{q}) = \frac{ie}{2\pi^2\epsilon} \frac{\mathbf{v}(\mathbf{q}\mathbf{v})\epsilon - \mathbf{q}}{\mathbf{q}^2 - (\mathbf{q}\mathbf{v})^2\epsilon} \tag{2.2}$$

we can obtain equations from the wave equation for the population amplitude $b(\mathbf{R},t)$ of the first excited level of an atom of the base material

$$i\frac{\partial b_1(\mathbf{R}, t)}{\partial t} = -\mathbf{D}_{10}\mathbf{E}_p(\mathbf{R}, t)e^{i\Omega_{10}t} + \sum_b V(\mathbf{R} - \mathbf{R}_b) b_1(\mathbf{R}_b, t), \tag{2.3}$$

where $V(\mathbf{R}_{ab})$ is the potential of a resonance dipole-dipole interaction, which has the following form at large distances:

$$V(\mathbf{R}_{ab}) = -R_{ab}^{-3}\{\mathbf{D}_{10}^{a}\mathbf{D}_{10}^{b} - 3(\mathbf{n}_{ab}\mathbf{D}_{10}^{a})(\mathbf{n}_{ab}\mathbf{D}_{10}^{b});\ \mathbf{R}_{ab} \equiv \mathbf{R}_{a} - \mathbf{R}_{b} \equiv \mathbf{n}_{ab}|\mathbf{R}_{ab}| \tag{2.4}$$

and which gives rise to a transfer of excitation from one atom to another and hence to a migration of excitation along the material. After analyzing one impurity atom in the material, we can write an equation for the population amplitude $a_3(\mathbf{R},t)$ of the E_3 state in the form

$$i\frac{\partial a_3(\mathbf{R},t)}{\partial t} = -\mathbf{d}_{30}\mathbf{E}_p(\mathbf{R},t)e^{i\omega_{30}t} + \left(\frac{d_{30}}{D_{10}}\right)\sum_b V(\mathbf{R}-\mathbf{R}_b)b_1(\mathbf{R}_{b_1}t), \tag{2.5}$$

where $\mathbf{d}_{30}$ is the matrix element of a transition in the impurity and $\mathbf{D}_{10}$ is the matrix element of a transition in an atom of the base material. In a homogeneous material we can substitute integration for summation over the atoms and then solve Eqs. (2.3) and (2.5) by using a Fourier transform with respect to the coordinates and time

$$b_1(\mathbf{q},\omega) = -\frac{\mathbf{D}_{10}\mathbf{E}_p(\mathbf{q})}{\omega - n_0(2\pi)^3 V(\mathbf{q})}\,\delta(\omega + \Omega_{10} - \mathbf{qv}), \tag{2.6}$$

where n_0 is the number of atoms of the material per unit volume,

$$\omega a_3(\mathbf{q},\omega) = -\mathbf{d}_{30}\mathbf{E}_p(\mathbf{q})\delta(\omega + \omega_{30} - \mathbf{qv}) + n_0(2\pi)^3\frac{d_{30}}{D_{10}}V(\mathbf{q})b_1\mathbf{q},\omega), \tag{2.7}$$

so that for $\omega_{30} = \Omega_{10}$

$$a_3(\mathbf{q},\omega) = -\frac{1}{\omega}\mathbf{d}_{30}\mathbf{E}_p(\mathbf{q})\frac{\omega - (1-(d_{30}/D_{10}))n_0(2\pi)^3 V(\mathbf{q})}{\omega - n_0(2\pi)^3 V(\mathbf{q})}\delta(\omega + \omega_{30} - \mathbf{qv}). \tag{2.8}$$

3. The 3-0 transition in an impurity atom gives rise to a transfer of excitation to the atoms of the base material; a 3-1 transition with an emission of a quantum can occur without a field. Since the E_1 state is orthogonal to the original ground state E_0, this emission is incoherent. The 3→1 and 1→2 transitions occur as a result of the action of the fields E_0 and E_1, after which the 2→0 transition with an emission of a quantum $\mathbf{k}$, ω is possible. The final state of an impurity in this case is the ground state, i.e., it coincides with the initial state, which allows a coherent radiation from different impurity atoms. Because of the influence of the excited atoms of the base material, we can assume that the emission of a quantum by an impurity atom has almost no influence on the population amplitudes $a_3(\mathbf{R},t)$ of the E_3 state. Retaining only the resonance terms, we can write the equations for the population amplitudes $a_2(\mathbf{R},t)$ and $a_1(\mathbf{R},t)$ of the E_2 and E_1 states of an impurity atom in the form

$$i\frac{\partial a_2(\mathbf{R}, t)}{\partial t} = -d_{21}E_0 \exp(i\mathbf{k}_0\mathbf{R})\, a_1(\mathbf{R}, t), \tag{3.1}$$

$$i\frac{\partial a_1(R_1 t')}{\partial t} = -d_{12}E_0 \exp(-i\mathbf{k}_0\mathbf{R})\, a_2(\mathbf{R}, t) - d_{13}E_1 \exp(-i\mathbf{k}_1\mathbf{R})\, a_3(\mathbf{R}, t)$$

where

$$a_2(\mathbf{R}, \omega) = \frac{(d_{21}E_0)(d_{13}E_1)}{\omega^2 - |d_{21}E_0|^2}\, a_3(\mathbf{R}, \omega) \exp\{i(\mathbf{k}_0 - \mathbf{k}_1)\mathbf{R}\}. \tag{3.2}$$

It follows from Eq. (3.2) that the Fourier component of the dipole moment induced in the impurity atom in the frequency region $\omega \approx \omega_{20}$ has the form

$$\mathbf{d}(\mathbf{R}, \omega) = \frac{d_{02}(d_{21}E_0)(d_{13}E_1)}{(\omega - \omega_{20})^2 - |d_{21}E_0|^2}\, a_3(\mathbf{R}, \omega - \omega_{20}) \exp(i\{\mathbf{k}_0 - \mathbf{k}_1)\mathbf{R}\}. \tag{3.3}$$

The total magnetic field produced by impurity atoms at the $\mathbf{R}_a$ points is determined by the expression ($R \gg R_a$, $\mathbf{n} \equiv \mathbf{R}/R$)

$$\mathbf{H}(\mathbf{R}, \omega) = R^{-1} \exp(i\omega\sqrt{\epsilon}R) \sum_a [\mathbf{n}\mathbf{d}(\mathbf{R}_a, \omega)] \exp(-i\mathbf{k}\mathbf{R}_a). \tag{3.4}$$

The coherent radiation is determined by the average field. Assuming that the impurity atoms are distributed uniformly with a density n_1, we can obtain the average field

$$\mathbf{H}(\mathbf{R}, \omega) = R^{-1} \exp(i\omega\sqrt{\epsilon}R)\, \omega^2 \sqrt{\epsilon} n_1 (2\pi)^3 \frac{[\mathbf{n}d_{02}](d_{21}E_0)(d_{13}E_1)}{(\omega - \omega_{20})^2 - |d_{21}E_0|^2} \times a_3(\mathbf{k} + \mathbf{k}_1 - \mathbf{k}_0, \omega - \omega_{20}). \tag{3.5}$$

Substituting Eq. (2.8) in Eq. (3.5), we obtain an expression for the energy that is coherently emitted by impurity atoms in the frequency range $d\omega$ in the $\mathbf{n}$ direction of the solid angle $d\Omega$

$$\frac{d\mathcal{E}}{d\omega d\Omega} = \frac{n_1^2 \omega^4 \sqrt{\epsilon} T (2\pi)^5}{(\omega - \omega_{20})^2 + \gamma_2^2} \left| \frac{[\mathbf{n}d_{02}](E_0 d_{21})(E_1 d_{13})(d_{30}E_p(\mathbf{k} + \mathbf{k}_1 - \mathbf{k}_0))}{\omega - \omega_{20} - |d_{21}E_0|^2} \right|^2 \times \left| \frac{\omega - \omega_{20} - n_0(2\pi)^3 V(\mathbf{k}_1 + \mathbf{k} - \mathbf{k}_0)(1 - [d_{30}/D_{10}])}{\omega - \omega_{20} - n_0(2\pi)^3 V(\mathbf{k}_1 + \mathbf{k} - \mathbf{k}_0)} \right|^2 \times \delta(\omega + \omega_1 - \omega_0 - \mathbf{k}\mathbf{v} + \mathbf{k}_0\mathbf{v} - \mathbf{k}_1\mathbf{v}), \tag{3.6}$$

where T is the total transit time of a particle and y_2 is the width of the E_2 level.

4. As seen in Eq. (3.6), the coherent radiation is concentrated near the frequency ω_{20} and near the angle of emission θ, which is determined by the delta function

$$\cos\theta = \frac{1}{v\sqrt{\epsilon}}\left\{1 - \frac{1}{\omega}(\omega_0 - \mathbf{k}_0\mathbf{v} - \omega_1 + \mathbf{k}_1\mathbf{v})\right\}. \tag{4.1}$$

This enables us to observe the coherent radiation against a background distributed over a wide range of angles of incoherent emission of the excited impurity atoms. Note that for $\omega_0, \omega_1 \to 0$ Eq. (4.1) becomes the well-known expression for the angle of emission of the Cerenkov radiation,[3] which, from the microscopic point of view, also represents a coherent de-excitation of the atoms of a substance that were excited by a particle. The limits of applicability of Eq. (3.6) are limited by fairly large fields $\mathbf{E}_0$ and $\mathbf{E}_1$, so that the field can have time to effect a resonance transfer of an electron to a different state during the lifetime of the y_2^{-1} state.

We can see from the above discussion that a coherent scintillator, in principle can be constructed in an external resonance field. Such a scintillator would make it possible to increase the intensity and decrease the de-excitation time. This scintillator can also be controlled by varying the field.

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