THE OPTO-ACOUSTIC MASER EFFECT

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It is shown that by employing multi-quantum transitions in discrete energy systems it should be possible to obtain coherent sources of radiation of various types in which the energy of the optical quantum is used.

LET a system H_c with discrete energy levels $E_1 < E_2 \ll E_3$ be exposed to the action of the radiation from a laser of frequency ν_1 ($\hbar\omega_1 \gtrsim E_3 - E_1$) and to a perturbation H_2 at frequency ν_2, for which $\langle 1 | H_2 | 2 \rangle \neq 0$, $\hbar\omega_1 = \hbar\omega_2 + E_3 - E_1$, where $\hbar$ is Planck's constant, and $\langle | \rangle$ is a matrix element. The system of levels E_i is chosen in such a way that $\langle 1 | \mu_\alpha | 3 \rangle = 0$, but $\langle 2 | \mu_\alpha | 3 \rangle \neq 0$, where μ_α is the operator of the electric (μ_e) or magnetic (μ_M) dipole. Then there is a non-zero probability for a transition of the system from the level E_1 to the level E_3 ($w_{1\to 3}$) with the participation of the virtual state $| 2 \rangle$ [1]. This process involves the annihilation of an electromagnetic quantum $\hbar\omega_1$, the emission of a quantum $\hbar\omega_2$, whose nature is determined by H_2, and the transition of a system to the excited state E_3 (i.e., the creation of a magnon—a quantum of potential energy). If the system H_c is put in a suitable cavity and the conditions for self-excitation are satisfied, one has an arrangement for generating coherent monochromatic quanta $\hbar\omega_2$ using the energy of the optical pump.

This multiple-quantum maser effect exhibits a number of features which differ advantageously from single quantum effects (masers, lasers). (1) Whereas in the well-known single-quantum masers the generation of phonons directly from photons is impossible (phonons are generated from magnons), the process is possible for the multiple-quantum maser effect, since virtual magnons are involved in these processes. (2) This effect occurs for the normal populations of the levels, determined by the Boltzmann factor. (3) The effect may be observed at moderate temperatures of the working substance. (4) It is a very promising mechanism for opening up the millimeter and submillimeter regions of the electromagnetic spectrum and for the production of hypersonic vibrations and microwave frequencies (up to the Debye frequency), since for a single pumping frequency ν_1 (for example the ruby laser) one may vary the difference $E_3 - E_1$ ($E_i - E_j = \hbar\omega_{ij}$) very widely.

As an illustration we derive the condition for self-excitation of hypersonic vibrations in a sample of Al_2O_3 with the impurity Cr^{3+}, in a strong magnetic field directed along the trigonal axis of the crystal and irradiated by the σ^+ (right circularly polarized) component of the output of a laser. In this case $E_1 = {}^4A_2(-3/2)$, $E_2 = {}^4A_2(1/2)$ and $E_3 = 2\bar{A}(^2E)$; $\nu_{31} \sim 10^{15}$ cps, $\nu_{21} \sim 10^{11}$ cps, $\langle 1 | \mu_e | 3 \rangle = 0$, $\langle 2 | \mu_e | 3 \rangle \sim 4 \times 10^{-21}$ esu.[2] The acoustic transitions $1 \longleftrightarrow 2$ are described by the operator $H_2 = \epsilon GL$ where ϵ is the strain tensor, G ($\sim 1.3 \times 10^{-15}$ ergs) is the constant of the spin-phonon interaction[3], and L is a bilinear function of the spin variables. The process of interest to us consists of the creation of a phonon of frequency $\nu_2 = \nu_1 - \nu_{31}$, the creation of a quantum of energy of the electric dipole of the Cr^{3+} ion, and the annihilation of a photon $\hbar\omega_1$. To calculate the probability per unit time for such a process for a single Cr^{3+} ion we make use of formula (7) from [1]. Evaluating this formula for our particular case gives

$$w_{1\to 3} = 3\omega_{21}^3 G^2 E^2 |\langle 1 | H_2 | 2 \rangle|^2 |\langle 2 | \mu_э | 3 \rangle|^2 [n(\nu_{21}) + 1] + [2\hbar^3 \pi d v^5 (\omega_1 + \omega_{32})^2]^{-1},$$

$$|\langle 2 | \mu_э | 3 \rangle|^2 = 3hc^3 [64\pi^4 \tau_{32} \nu_{32}^3]^{-1}, \quad \rho(\nu_{21}) = 12\pi V \nu_{21}^2 v^{-3},$$

$$|\langle 1 | H_2 | 2 \rangle|^2 = \hbar^2 [n(\nu_{21}) + 1][\coth(\hbar\omega_{21}/kT)\, \tau_{21} \rho(\nu_{21})]^{-1}, \quad (1)$$

where T is the temperature, k is the Boltzmann constant, d is the density of the crystal, v is the velocity of sound, E is the intensity of the optical electric field, $n(\nu_2)$ is the number of phonons of frequency ν_2, τ_{32} is the lifetime due to spontaneous radiation of the transition $3 \rightarrow 2$, τ_{21} is the single phonon-spin-lattice relaxation time, V is the volume of the crystal, and c is the velocity of light.

The condition for self-excitation from the zero-point vibrations of the lattice has the following form

$$N \geqslant C_0 \varepsilon^2 \left[Q(\omega_2) \hbar \omega_{1\to 3} \right], \quad \varepsilon^2 = \hbar\omega_2 \left[n(\nu_2) + 1 \right] (2Mv^2)^{-1}, \tag{2}$$

where N is the number of working particles per unit volume, C_0 is the modulus of elasticity, M is the mass of the crystal, and $Q(\omega_2)$ is the acoustical Q of the crystalline resonator. For the case of high quality reflecting walls at helium temperatures[4]

$$Q(\omega) = Q_0(\omega) \left[1 + \frac{\delta}{T^4} \right], \quad \delta = \frac{\tau_0}{t} \frac{\lambda_\omega^3}{V} A, \quad \tau_0 = \frac{1}{\alpha_0 v}, \tag{3}$$

where $Q_0(\omega)$ and α_0 are the acoustic quality factor and absorption coefficient due to scattering at defects and rough surfaces, λ is the wavelength, $1/t$ is the repetition frequency of the acoustic pulses, and A is a constant related to the Grueneisen constant and the elastic constant.

Putting $v = 6 \times 10^5$ cm/sec, $C_0 = 10^{12}$ dyne/cm, $d = 3.896$ gm/cm^3 [5], $\nu_{21} = 10^{11}$ sec^{-1}, $Q(\omega_2) = 10^3$, $E = 10^2$ esu. we obtain

$$N \geqslant 10^{18} \text{cm}^{-3}, \tag{4}$$

which is less severe than the requirement for self-excitation of a phonon maser with microwave pumping[6].

The estimate given in (4) is not the optimum. For Fe^{2+} in MgO we have $G \sim 10^{-13}$ erg, $Q_0(\omega) \sim 10^4$ for $\nu = 10^9$ cps in quartz, and $\delta \sim 1$ at 2° K, all of which may improve the estimate by a factor of 10^6 even at helium temperatures.

It seems to us that a system of hypersonic phonons produced by the opto-acoustic maser effect might have interesting scientific and practical applications; for example in the investigation of the Debye spectrum of crystals and the anharmonic vibrations of solids[4]. If the system is arranged so that the maser effect is possible only in the presence of an external perturbation, the apparatus may be used to detect extremely small deformations.

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