Concerning one possibility of lasing in the gamma band

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1. Various possibilities of producing a γ-ray laser were discussed recently at the 3rd Vavilov Conference on Nonlinear Optics.[1-3] It is generally conceded that the Mössbauer effect must be used to develop a γ laser. Taking into account the pump powers attainable in practice, it is necessary to use relatively long-lived isomers with level lifetimes $\sim 10^{-2}$ sec. To make lasing possible, the width of the gain line should be 10^4–10^5 Hz. To satisfy these requirements without special construction variants, the level excitation calls for a neutron flux attainable only in nuclear explosions, but under conditions that permit the use of the Mössbauer effect.[4,5] The use of longer-lived isomers makes it possible to lower the pump level, but makes it necessary to narrow down greatly the Mössbauer lines,[6,7] and this calls for the solution of a number of problems in crystal physics, in the Mössbauer effect, etc.

We propose here a new way of developing a γ laser, based on the use of resonant stimulated Raman scattering (SRS) in nuclear transitions. The stimulated Raman scattering makes it possible to use for the initial state long-lived isomers with lifetimes ~ 1–10^5 sec and obtain amplification on transitions with a short-lived upper level having a lifetime 10^{-7}–10^{-15} sec. These requirements were mutually contradictory in the previously proposed γ-laser variants.

2. The nuclear-transition scheme considered here is shown in the figure. Level 1 is long-lived and is excited by various methods. The long-wave radiation of frequency ω is at resonance with the $0 \to 1$ transition of frequency ω_{01}. The Raman scattering is observed on the transition $0 \to 2$, with $\omega_{02} \gg \omega_{01}$. The final probability γ_{01} of the decay from the level 0 to the level 1 changes the kinetics of the excited transitions. To determine the gain α of the spectral component in the transition $0 \to 2$, one uses the standard procedure of solving the equations for the density matrix. The relaxation constant of the level 1, which enters in the equations, is determined not by the lifetime of the level 1, but by the time of interaction $\tau_1 = 1/\gamma_1$ of the nucleus with the field. This time is connected with the path length, with the collisions, etc., and can be smaller by many orders of magnitude than the lifetime of the level 1. It will be shown below that this circumstance, which is peculiar to a gas, plays the decisive role in the considered γ-laser variant. We present the results of the calculations when1) $\gamma_1 + \gamma_2 \ll \omega_0 = (\omega_{02}/\omega_{01})\omega_g$ and $\gamma_1 + \gamma_2 \ll \gamma_0$ (γ_0 and γ_2 are the reciprocal lite-times of the levels 0 and 2, while $\omega_g = \omega_{01}(v_0/c)$ and v_0 is the thermal velocity:

$$a = a_0 \frac{(\gamma_0/2)^2}{\left(\frac{\omega_{01}\cos\theta}{\omega_{02}}\Omega' - \Omega\right)^2 + (\gamma_0/2)^2} \exp\left[-\left(\frac{\Omega' - \Omega}{\omega_0}\right)^2\right]$$

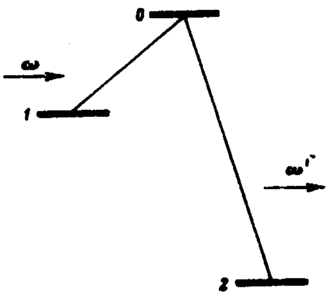
$$2)\ \omega_g \sin\theta >> \gamma_0, \tag{1}$$

$$a = a_0 \frac{\gamma_0}{\omega_g \sin\theta} \times \exp\left[-\left(\frac{\omega_{01}\cos\theta}{\omega_{02}}\Omega' - \Omega\right)^2 \Big/ (\omega_g \sin\theta)^2\right] \exp\left[-\left(\frac{\Omega'}{\omega_0}\right)^2\right], \tag{2}$$

$$a_0 = \frac{\lambda'^2 \gamma_{02}}{\gamma_0} \frac{\omega_{01}}{\omega_{02}} \frac{1}{\gamma_0} \frac{\gamma_0 - \gamma_{01} + \gamma_1}{\gamma_0} \frac{\lambda^2 n \gamma_{01}}{\omega_g} \frac{I}{\hbar\omega}, \tag{3}$$

where θ is the angle between the propagation directions of the incident and induced radiation, $\Omega' = \omega' - \omega_{02}$, $\Omega = \omega - \omega_{01}$, γ_{01} and γ_{02} are the probabilities of the transitions $0 \to 1$ and $0 \to 2$, the inequality $\gamma_0 \geq \gamma_{01} + \gamma_{02}$ takes into account the internal conversion, λ and λ' are the wavelengths of the incident and scattered field, respectively, n is the density of the nuclei excited at the level 1 (in cm^{-3}), and I is the energy flux density (erg/cm^{2}sec) of the external field at the frequency ω; the expression for α_0 is accurate to within a factor that is immaterial for the estimates. The saturation on the $0 \to 1$ transition is small, i.e.,

$$\kappa = \frac{\lambda^2 \gamma_{01}}{\gamma_0 \gamma_1} \frac{\gamma_0 - \gamma_{01} + \gamma_1}{\gamma_0} \frac{I}{\hbar\omega} << 1. \tag{4}$$



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3. Let us estimate the incident-radiation power needed to obtain generation. Let monochromatic x rays of wavelength $\lambda = 10^{-7}$ cm (~ 1 keV) lead to SRS of γ radiation with $\lambda' = 10^{-9}$ cm (~ 100 keV). For generation to take place it is necessary that the gain (1) compensate for the losses due to absorption and scattering of the photon in the gas. The gain (per unit length) for $\lambda' = 10^{-9}$ cm is determined by the photoelectric absorption and is equal to $n\sigma$, where $\sigma \sim 10^{-22}$ cm^2 [9] (for estimates, we assume the gas to be fully isomeric). If we assume $\gamma_{01} \sim \gamma_{02} \sim \gamma_0$. $\omega_g \sim 10^{10}$ Hz($v_0 \sim 10^3$ cm/sec), then we obtain from the generation condition $a_0 = n\sigma$ the value $I \sim 10^6$ W/cm^2. At a beam cross section $\sim 10^{-4}$ cm^2 we obtain a small pump power, $P \sim 10^2$ W.

The pumping time $\tau_1 = 1/\gamma_1$ needed to maintain the stationary regime is obtained from the condition $\kappa \sim 1$. Using (4), we get $\tau_1 \sim 10^{-8}$ sec. If we choose a laser length $L = 10$ cm, then we can assume a beam diameter $d \sim \sqrt{\lambda L'} \sim 10^{-4}$ cm. The density of the excited and nuclei does not influence the generation condition, and therefore choose n such that the entire incidenc power is absorbed over a length d. Since the absorption coefficient per unit length is $\beta = \lambda^2 n \gamma_0/\omega_g$, we get $n \sim 10^{18}\omega_g/\gamma_0$ at $\beta d \sim 1$.

Let us discuss a question of how to supply the required pump power. If $\omega_g \lesssim \gamma_0$, then the required excitation rate can be obtained by pumping the gas through at a rate $v = d/\tau_1 = 10^4$ cm/sec. At $\omega_g \gg \gamma_0$, the number of nuclei interacting with the radiation is $n\gamma_0/\omega_g$. The collisions lead to a velocity redistribution within a time $\tau \sim 1/n v_0 \sigma_t \sim 10^{-6}\ \gamma_0/\omega_g$ ($\sigma_t \sim 10^{-15}$ cm^2 is the gaskinetic cross section), and to obtain $\tau \lesssim \tau_1$ we need $\gamma_0/\omega_g \lesssim 10^{-2}$. The nuclei will now "burn out" in the beam within a time $\tau \sim \tau_1 \omega_g/\gamma_0$, and their arrival in this region can be ensured within a time $t_g \sim d^2/D$ ($D \sim v_0/n\sigma_t$ is the diffusion coefficient). At $\gamma_0/\omega_g \sim 10^{-3}$ we have $t \sim t_g \sim 10^{-5}$ sec, i.e., the generation will be stationary.

4. We can indicate a number of concrete nuclear transitions corresponding to the three-level scheme at $\omega_{02} \gtrsim \omega_{01}$. For example, in Te^{125} the excited level of energy 145 keV has a lifetime of 58 days. The 641-keV level can decay to the 35-keV level ($\gamma_{02} \sim 10^{10}$ sec^{-1}).[10] The choice of the concrete scheme with $\omega_{02} \gg \omega_{01}$ turned out to be difficult.

5. The considered generation method can be used to obtain ultraviolet and x radiation by using electronic transitions of multiply-charged ions. The choice of the concrete scheme is much easier in this case.

1) Under resonance conditions, when the intermediate level is short-lived in comparison with the initial level ($\gamma_0 \gg \gamma_1$), the stimulated emission at an adjacent transition is determined by two-quantum transitions (SRS).[8] The contribution of single-quantum transitions can be neglected. To obtain gain in this case it is necessary to have inversion between levels 1 and 2, whereas inversion between levels 0 and 2 is not obligatory. In the optical band, lasing at resonant SRS on excited atoms, with conversion of the radiation into shorter wavelengths, was observed in[11]. The possibility of obtaining short-wave generation by a three-level scheme on helium-atom transitions was considered in[12] in connection with the problem of atom acceleration by an optical field. Lasing following multiphoton absorption of long-wave radiation from the ground state of the atoms was observed in[13].

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