Proposal for high-power radiative-collisional lasers

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We propose the use of the radiative-collisional laser process for the extraction of energy that is stored in the resonance lines of the alkali atoms. The largest calculated gain occurs in Rb at 5.4 μm and is 8%/cm at a resonance-line population of 5×10^{16} atoms/cm^3.

In this Letter we propose the use of the radiative-collisional laser process[1] for the extraction of energy that is stored in the resonance lines of the alkali atoms. The Letter is in part motivated by a recent experiment with a pulsed hollow-cathode discharge, in which Falcone and co-workers[2] obtained a population in the upper level of the resonance line of lithium of 4×10^{16} atoms/cm^3, corresponding to a stored energy density of about 0.01 J/cm^3. This population is stable for a 75-nsec period and occurs under conditions in which the (measured) population of higher levels, for example the Li ($1s^23p$) and Li ($1s^23d$) levels, are much lower (about 10^{13} atoms/cm^3).

Radiative-collisional gain is closely related to the laser-induced collision process that has been studied extensively during the last several years.[3-6] A prototype of the alkali-atom systems that we are considering is shown in Fig. 1. Initially, two atoms are excited by a discharge to the $3p\ ^2P_{1/2}$ level of the sodium resonance-line transition. During the collision between the excited atoms, dipole–dipole coupling causes a simultaneous transition of one atom to the ground level and the other atom to a virtual level (shown by the dashed line), which has $4d$ character. The radiative-collisional process is completed by the emission of a photon at 2.7 μm, thereby resulting in the deexcitation of both resonance-line atoms.

The photon at 2.7 μm may be emitted spontaneously[4] or, of interest to us here, may be stimulated. The line shape for both spontaneous emission and gain will center at a frequency equal to twice that of the resonance line minus that of the terminal level and for the systems considered here will have a width of 10–20 cm^{-1}. The requirement for net radiative-collisional gain is that the product of the density of the excited resonance atoms exceed the product of ground- and final-level ($1s^24p\ ^2P^\circ{}_{1/2}$) densities. A radiative-collisional laser is homogeneously broadened and, once threshold is reached, gain narrowing will occur.

For optical power densities in the range where the cross section for laser-induced collision varies linearly with power density, the per-length gain (or loss) coefficient for a radiative-collisional laser may be written[4,7] (in mks or cgs units) as

$$G = \frac{32\pi^2}{81\hbar^3}\frac{S_{12}S_{34}S_{45}}{g_4\Delta\omega^2 c\bar{V}\rho_0{}^2}\left(\frac{N_1N_3}{g_1g_3} - \frac{N_2N_5}{g_2g_5}\right), \qquad (1)$$

where S_{ij}, g_i, and N_i are the line strengths, degeneracies, and populations, respectively, of the pertinent transitions and levels (Fig. 1); $\Delta\omega$ (rad/sec) is the detuning of the virtual level from the real level of the same symmetry (636 cm^{-1} in Fig. 1); $\bar{V}$ is the average thermal velocity of the atoms; and ρ_0 is the characteristic dephasing or Weisskopf radius. Atoms that approach one another with an impact parameter less than this radius are dephased by more than 1 rad and make a negligible contribution to the radiative-collisional gain. For the systems that we study here, this radius is calculated from the formula

$$\rho_0{}^5 - \frac{2C_3}{\hbar\bar{V}}\rho_0{}^3 + \frac{3\pi C_6}{8\hbar\bar{V}} = 0, \qquad (2)$$

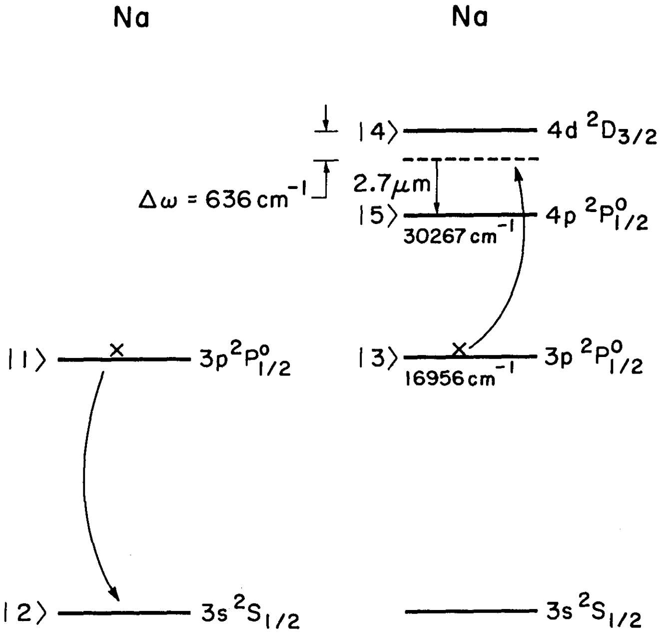

Fig. 1. Prototype system for alkali-atom radiative-collisional laser.

Table 1. Alkali-Atom Radiative-Collisional Lasers

Element and Storage Level[a]	λ (μm)	ρ_0 (Å)	g (cm^{-1})[b]
Na (1/2, 1/2)	2.7	15.0	1.4×10^{-3}
Rb (3/2, 3/2)	5.4	15.7	8.0×10^{-2}
Rb (1/2, 3/2)	6.3	16.0	3.4×10^{-3}
Cs (3/2, 3/2)	6.6	20.6	3.6×10^{-3}
Cs (1/2, 3/2)	10.3	27.9	1.1×10^{-2}

[a] In all cases the storage levels are the ^2P_J levels of the resonance line, where J is indicated in column 1.

[b] The gain (per centimeter) is calculated with an assumed storage density of 5×10^{16} atoms/cm^3.

where C_3 and C_6 are the resonant and nonresonant interaction energies of the coupled energy levels.

Table 1 gives the results of our calculations for a number of alkali systems. We limit our discussion to systems in which only a single element is used and in which storage is in the resonance level of the atom. The particular fine-structure component of the $np\,^2P$ level in each of the atoms is denoted in column 1. The calculated gain (per centimeter) assumes a storage density of 5×10^{16} atoms/cm^3 in each of the storage levels and varies as the square of this number.

The largest gain among the systems that were calculated occurs in Rb at 5.4 μm. At the assumed population of 5×10^{16} atoms/cm^3, a 1-m-long, 1-cm-diameter discharge will have a gain of e^8 and an extractable per-pulse energy of 75 mJ.

The parameter ρ_0 in the third column of Table 1 gives a guide to the maximum rate of energy extraction from the system. At large power densities (for these systems, typically 10^9 W/cm^2), the cross section for laser-induced collision is several times $\pi\rho_0^2$. At a gas density of 5×10^{16} atoms/cm^3, this corresponds to a collision frequency of about 10^9 and therefore to a maximum energy-extraction rate of about 1 nsec.

Radiative-collisional lasers with resonance-line storage offer the possibility of efficient conversion of electrical to optical energy. We have limited the discussion to systems that employ only a single alkali element and in which the terminal level is high in the manifold. If one allows for mixed systems, and for elements other than the alkalis, there is a possibility of fabricating lasers with wavelengths throughout much of the visible and near-infrared region. As a result of the greater detunings in these systems, the calculated gains are usually a factor of 10 smaller than those of the systems studied here.

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