# Inversionless gain in a three-level system driven by a strong field and collisionsProject supported in part by the Russian Foundation for Basic Research (Grant No. 96-00010c), by the National Natural Science Foundation of China (Grant No. 19911121500) and by the Science and Technology Foundation of Jilin Province, China (Grant No. 980526).

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# INVERSIONLESS GAIN IN A THREE-LEVEL SYSTEM DRIVEN BY A STRONG FIELD AND COLLISIONS*

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Inversionless gain in a degenerate three-level system driven by a strong external field and by collisions with a buffer gas is investigated. The mechanism of population distribution in upper laser level, contributed by the collision transfer, as well as by relaxation, induced by pressure of a buffer gas, is discussed in detail. Explicit formulae for analysis of optimal conditions are derived. The idea developed here for the incoherent pump could be generalized to other systems.

**PACC:** 4250; 3150

## I. INTRODUCTION

Light amplification without population inversion (AWI) has been studied in a number of theoretical and experimental papers [1–32] because of its potential application in producing high-power lasers in the regions of electromagnetic spectrum which are difficult to reach with traditional laser system. Although population inversion between the laser levels is not necessary in an inversionless light amplification system, it is required to pump a fraction of population to the upper level incoherently. Possible AWI at the transitions between excited states of noble gases, pumped by discharge, was shown in Refs.[1,20]. The incoherent pumping by discharge may not always provide necessary population, and the direct excitation by laser with broad linewidth may introduce additional atomic coherence. Another approach to possible AWI assisted by the collisional population transfer between fine structure levels of alkali atoms was proposed in Refs.[12–14] and successful experiments[33,34] proved that wide range manipulation by population of the levels (up to population inversion) can be provided with this mechanism. Successful experiments on AWI in potassium vapors based on such mechanism were reported in Ref.[21]. (The theory and estimates for sodium atoms, underlying Refs.[12–14] were presented in Refs.[25,28] too). Hyperfine structure of D-lines in alkalies and degeneracy of the coupled levels require multilevel model in order to consider the complex of quantum nonlinear coherence and interference effects, which are the origin of AWI. However experiments with sodium[22] and potassium[21] atoms showed, that major behavior and requirements for AWI (especially at detuning of the driving field from the resonance) may be studied with the aid of simple three-level V-configuration. In this paper, the mechanism of incoherent pumping by a strong laser beam and collisional population transfer induced by buffer gas pressure is further analyzed. In order to fit better experimental conditions degeneracy are taken into account. We derived simple and explicit formulae describing the process. With the aid of these expressions we compare various alkalies and buffer gases in order to show that strong competition between population transfer and loss of coherence may be optimize by proper choice of the transitions and buffer gases. The idea developed here for incoherent pumping could be generalized to other systems.

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## II. THEORETICAL MODEL AND EQUATIONS

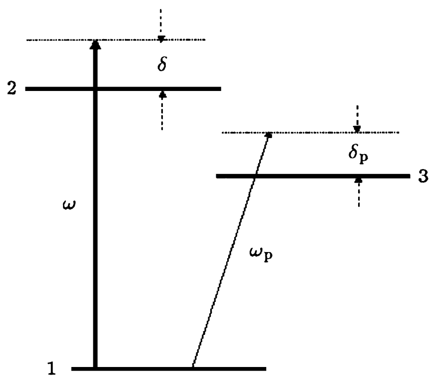


**Fig.1.** Level scheme for inversionless amplification in the collision- driven three-level system. Transition $|3\rangle$–$|1\rangle$ is probed by the week radiation at the frequency $\omega_{\mathrm{p}}$. Transition $|2\rangle$–$|1\rangle$ is coupled to the strong radiation at the frequency $\omega$. Level $|1\rangle$ is ground state, $|2\rangle$ and $|3\rangle$ are fine splitting levels. In order to manipulate by the population difference at the probe transition in the wide range from positive (absorption) via zero to negative values (gain), while maintaining absorption at the coupled transition, we propose making use energy-transferring collisions with atoms of a buffer gas along with the saturation effects. Near Boltzmann's population distribution between fine-structure levels may set up due to the collisions.

We consider a model as shown in Fig.1 which consists of three levels labeled $|1\rangle$, $|2\rangle$ and $|3\rangle$. A strong driving field with frequency $\omega$ produces coherent coupling between levels $|1\rangle$ and $|2\rangle$, while the weak probe field with frequency $\omega_{\mathrm{p}}$ is scanned around the transition between levels $|3\rangle$ and $|1\rangle$. We express the probe and driving fields in the form

$$E_{\mathrm{p}}(t)=\frac{1}{2}[E_{p0}(t)\mathrm{e}^{-\mathrm{i}\omega_{\mathrm{p}}t}+\mathrm{c.c.}], \tag{1}$$

$$E(t)=\frac{1}{2}[E_0(t)\mathrm{e}^{-\mathrm{i}\omega t}+\mathrm{c.c.}], \tag{2}$$

where $E_{\mathrm{p}}(t)$ and $E(t)$ are the slowly varying complex amplitudes. The Hamiltonian of the system including the interaction between the atom and the two fields can be written as

$$\begin{aligned} H=&H_a+H_b,\\ H_a=&\hbar\omega_{\mathrm{p}}a_3^+a_3+\hbar\omega a_2^+a_2,\\ H_b=&-\hbar\delta_{\mathrm{p}}a_3^+a_3-\hbar\delta a_2^+a_2\\ &-\hbar[g_{\mathrm{p}}a_3^+a_1\mathrm{e}^{-\mathrm{i}\omega_{\mathrm{p}}t}+ga_2^+a_1\mathrm{e}^{-\mathrm{i}\omega t}+\mathrm{c.c.}], \end{aligned} \tag{3}$$

where $\delta_{\mathrm{p}}=\omega_{\mathrm{p}}-\omega_{31}$, $\delta=\omega-\omega_{21}$; $\omega_{31}$ and $\omega_{21}$ denote the transition frequencies from $|3\rangle$ to $|1\rangle$ and $|2\rangle$ to $|1\rangle$, respectively; $g=\mu_{21}E_0/2\hbar$, $g_{\mathrm{p}}=\mu_{31}E_{\mathrm{p}0}/2\hbar$ are the Rabi frequencies of the probe and the driving fields, respectively; $\mu_{31}$ and $\mu_{21}$ are the dipole matrix elements of optical transitions from $|3\rangle$ to $|1\rangle$ and $|2\rangle$ to $|1\rangle$, respectively. In the interaction picture, the master equation for the density operator is

$$\frac{\mathrm{d}r}{\mathrm{d}t}=-\frac{\mathrm{i}}{\hbar}[\widetilde{H_b},r]+\text{incoherent term}, \tag{4}$$

where $r=\mathrm{e}^{\mathrm{i}H_at/\hbar}\rho\mathrm{e}^{-\mathrm{i}H_at/\hbar}$, $\widetilde{H}_b=\mathrm{e}^{\mathrm{i}H_at/\hbar}H_b\mathrm{e}^{-\mathrm{i}H_at/\hbar}$. According to Eq.(4), the matrix elements of the density operator can be expressed as follows:

$$\begin{aligned} \frac{\mathrm{d}r_{31}}{\mathrm{d}t}&=\mathrm{i}g_{\mathrm{p}}(r_1-r_3)-(\Gamma_{31}-\mathrm{i}\delta_{\mathrm{p}})r_{31}-\mathrm{i}gr_{32},\\ \frac{\mathrm{d}r_{32}}{\mathrm{d}t}&=\mathrm{i}gr_{21}^*-\mathrm{i}g^*r_{31}-[\Gamma_{23}-\mathrm{i}(\delta_{\mathrm{p}}-\delta)]r_{32},\\ \frac{\mathrm{d}r_{21}}{\mathrm{d}t}&=\mathrm{i}g(r_1-r_2)-(\Gamma_{21}-\mathrm{i}\delta)r_{21}-\mathrm{i}g_{\mathrm{p}}r_{32}^*,\\ \frac{\mathrm{d}r_3}{\mathrm{d}t}&=2\mathrm{Im}(g_{\mathrm{p}}^*r_{31})-\Gamma_3r_3+w_{23}r_2,\\ \frac{\mathrm{d}r_2}{\mathrm{d}t}&=2\mathrm{Im}(g^*r_{21})-\Gamma_2r_2+w_{32}r_3, \end{aligned} \tag{5}$$

$$r_1+r_2+r_3=1. \tag{6}$$

Here $r_{ij}=r_{ji}^*$, $r_{ii}=r_i$, $\Gamma_2=A_{21}+w_{23}$, $\Gamma_3=A_{31}+w_{32}$, where $A_{21}$ and $A_{31}$ are the decay rates of populations in levels $|2\rangle$ and $|3\rangle$ to the ground state $|1\rangle$ due to the common spontaneous transition, respectively; $w_{23}$ and $w_{32}$ are the collision transfer relaxation rates of the populations in level $|2\rangle$ to level $|3\rangle$ and in level $|3\rangle$ to level $|2\rangle$ due to collision; $\Gamma_{21}$, $\Gamma_{31}$, and $\Gamma_{23}$ are the polarization decay rates between levels $|1\rangle$ and $|2\rangle$, levels $|3\rangle$ and $|1\rangle$, levels $|3\rangle$ and $|2\rangle$, respectively ($\Gamma_{ij}=\Gamma_{ji}$).

The absorption and refractive indices at the frequency $\omega_{\mathrm{p}}$ are determined by the complex susceptibility $\chi(\omega_{\mathrm{p}})$ which is proportional to the off-diagonal element $r_{31}$: $\chi(\omega_{\mathrm{p}})=(r_{31}\mu_{13})/(E_{\mathrm{p}}/2)$. In the linear approximation of the probe field, the steady state solution of Eq.(5) for $r_{31}$ is

$$r_{31}=\mathrm{i}\frac{g_{\mathrm{p}}(r_1-r_3)-gr_{32}}{\Gamma_{31}-\mathrm{i}\delta_{\mathrm{p}}}. \tag{7}$$

The coherence $r_{32}$ itself is dependent on $r_{31}$ and $r_{21}$. By substituting the solution for $r_{32}$ into Eq.(7) one obtains

$$\frac{\chi}{\chi_0}=f(\delta_{\mathrm{p}})=\mathrm{i}\Gamma_{31}\frac{[\Gamma_{23}-\mathrm{i}(\delta_{\mathrm{p}}-\delta)](r_1-r_3)-\mathrm{i}gr_{21}^*}{[\Gamma_{23}-\mathrm{i}(\delta_{\mathrm{p}}-\delta)](\Gamma_{31}-\mathrm{i}\delta_{\mathrm{p}})+|g|^2}, \tag{8}$$

where

$$r_{21}=-\mathrm{i}g(r_1-r_2)/(\Gamma_{21}-\mathrm{i}\delta). \tag{9}$$

Eventually from Eqs.(8),(9) we obtain

$$f(\delta_{\rm p}) = {\rm i}\Gamma_{31}\frac{[\Gamma_{23}-{\rm i}(\delta_{\rm p}-\delta)](r_1-r_3)-|g|^2(r_1-r_2)/(\Gamma_{21}+{\rm i}\delta)}{[\Gamma_{23}-{\rm i}(\delta_{\rm p}-\delta)](\Gamma_{31}-{\rm i}\delta_{\rm p})+|g|^2}, \tag{10}$$

and

$$\alpha_{\rm p}/\alpha_{\rm p0} = {\rm Im}f(\delta_{\rm p}), (n_{\rm p}-1)/(n_{\rm p\,max}-1) = {\rm Re}f(\delta_{\rm p}).$$

## III. MECHANISM OF POWER AND COLLISION DRIVEN AWI

Optimum conditions for AWI in three-level V configuration, assuming possible manipulation by populations of the coupled levels with incoherent pumping were analyzed in Ref.[1]. Classification of the effects of a strong field on the spectral line shape at an adjacent transition for various V, $\Lambda$ and H configurations of coupled transitions was given in Refs.[1,2] (see also Refs.[3](e) and [35]): dependence of $r_{i,j}$ and of the denominator in Eq.(8) on $g$ refers to saturation of populations and energy-level splitting effects, correspondingly; and $r_{21}$ represents the nonlinear interference effects (NIEF). As shown in Refs.[2] and [3](e), NIEF brings about change of the line shape but not the integral intensity

$$\int {\rm d}\delta_{\rm p} f(\delta_{\rm p}, |E|^2) = \pi\Gamma_{31}(r_1-r_3), \tag{11}$$

which depends only on saturation effects.

Indeed, NIEF represents the origin of sign-changing spectral line shapes and AWI at the probe transition. One can regard Eq.(8) as the difference between acts of pure emission (associated with the $r_3$, assuming $r_1 = r_2 = 0$), and pure absorption (the rest of terms). Both of them are positive but depend in a different way on detunings, because of NIEF. This was emphasized in Ref.[2] (see also Refs.[3] (e), [1,35]).

Thus, in the scheme under consideration AWI originates from the coherence at the transition $|3\rangle$–$|2\rangle$, induced by the strong field, coupled to the auxiliary level $|2\rangle$ in combination with the probe field, which consequently gives rise to the factor $r_{21}$ in Eq.(8). The larger the maximum value of $r_{21}$ compared to $r_1 - r_3$, the more pronounced is the effect of AWI. At $\delta = 0$, maximum of absorption (gain) corresponds to $\delta_{\rm p} = 0$:

$$f(0) = \frac{(r_1-r_3)-(r_1-r_2)S}{1+S}, \tag{12}$$

where $S = |g|^2/\Gamma_{21}\Gamma_{32}$. Therefore, even if $(r_1 - r_3) > 0$ and $(r_1 - r_2) > 0$, negative absorption (gain) occurs if

$$(r_1 - r_2)S > r_1 - r_3. \tag{13}$$

The less the coherence decay rate $\Gamma_{32}$ at the two-photon transition $|3\rangle$–$|2\rangle$, compared to that at the coupled one-photon transitions, the more favorable are the conditions for AWI. At $S > 1$ large splitting of the level $|1\rangle$ to two quasi levels significantly reduces interference and, therefore, the magnitude of AWI at the center of the transition $|3\rangle$–$|1\rangle$. Optimal value of strength of driving field for AWI in the probe line center was analyzed in Ref.[1].

Below we shall consider the opportunities and specific experimental scheme to control the shape of absorption and refraction indexes without external incoherent pumping. The distribution of populations necessary for AWI is ensured by collisions.

Consider alkali atoms immersed in a buffer gas. Strong field couples $P_{3/2}$ and ground $S$ levels. Fast collision exchange ensures population transfer from the $P_{3/2}$ to the lower $P_{1/2}$ level. In order to understand the main mechanism giving rise to AWI, suppose for simplicity, that the pressure of the buffer gas is so high, that Boltzmann population distribution between the fine structure levels is established. This leads to a means to control population difference at the probe transition in a wide range by increasing the intensity of the strong field. Even population inversion at the $P_{1/2}$–$S$ transition can be provided due to the saturation effect at $P_{3/2}$–$S$ transition (similar to that in ruby laser). Such a feasibility to produce population inversion at the transition $P_{1/2}$–$S$ has been demonstrated experimentally for potassium[33] and sodium[34] vapors admixed to helium at about atmospheric pressure. To make AWI possible, the required driving field strength and buffer gas pressure can be estimated as follows. One can find from the equation system (6)

$$r_2 = \frac{\Gamma_3}{2\Gamma_3+w_{23}}\frac{æ'}{1+æ'},\ r_3 = \frac{w_{23}}{\Gamma_3}r_2,\ r_1 = \left(1+\frac{\Gamma_3 æ'}{2\Gamma_3+w_{23}}\right)\frac{1}{1+æ'}; \tag{14}$$

$$r_1 - r_2 = \frac{1}{1+æ'},\ r_1 - r_3 = \left(1+\frac{\Gamma_3-w_{23}}{2\Gamma_3+w_{23}}æ'\right)\frac{1}{1+æ'}. \tag{15}$$

Here

$$æ' = \frac{2 + (w_{23}/\Gamma_3)}{[1 - (w_{32}w_{23}/\Gamma_3\Gamma_2)}æ, \quad (16)$$

$$æ = 2\Gamma|g|^2/\Gamma_2(\Gamma^2 + \delta^2). \quad (17)$$

Consider high pressure limit, assuming that $A_{31} \simeq A_{21}$, and the buffer gas pressure is so high, that $(w_{23} - w_{32}) \gg A_{31}, A_{21}$. Then taking into account that under the given conditions $w_{32} = w_{23}\exp(-\Delta E/k_{\rm B}T)$, where $\Delta E = E_2 - E_3$ is the fine splitting energy, $k_{\rm B}$ and $T$ are Boltzmann's constant and temperature, we obtain

$$r_1 - r_3 = \left[1 - æ'\frac{1 - \exp(-\Delta E/k_{\rm B}T)}{1 + 2\exp(-\Delta E/k_{\rm B}T)}\right]\frac{1}{1 + æ'}; \quad (18)$$

$$æ' = \frac{1 + 2\exp(-\Delta E/k_{\rm B}T)}{1 + \exp(-\Delta E/k_{\rm B}T)}\frac{2|g|^2\Gamma_{21}/A_{21}}{\Gamma_{21}^2 + \delta^2}. \quad (19)$$

For sodium $\Delta E = 17.2\,{\rm cm}^{-1}$ and at $T = 550\,{\rm K}$ the estimates give

$$\Delta E/k_{\rm B}T = 4.3 \times 10^{-2},$$

$$æ' \simeq 3|g|^2/\Gamma\Gamma_2 \simeq 9\lambda^3 I/64\pi^3\epsilon_0\hbar c\Gamma_{21},$$

$$r_1 - r_3 \simeq \frac{1}{1 + æ'}[1 - 1.3 \times 10^{-2}æ']. \quad (20)$$

Here $\lambda$ and $I$ are the strong field wavelength and the energy flux density, $\epsilon_0$ is the permittivity of free space. From the Eqs.(12),(18),(19) one can see that the potentially attainable AWI grows with the increase of $\Delta E$ (for example, in K and Rb). On the other hand, with the increase of fine splitting population transferring collision cross-section decreases. That must be compensated by increase of buffer gas pressure. The latter brings loss of coherence. Their inter dependence will be investigated numerically in the next section.

Inelastic collision crossection of sodium and helium for the transition $3P_{3/2} - 3P_{1/2}$ is $\sigma_{23} \simeq 4 \times 10^{-15}\,{\rm cm}^2$.[36] For $T$=550 K and atmospheric pressure of helium we estimate $w_{23} = N_{\rm He}\bar{v}\sigma_{23} \simeq 7.5 \times 10^9\,{\rm s}^{-1}$. Since $A_{31} \simeq A_{21} \simeq 6.2 \times 10^7\,{\rm s}^{-1}$, requirements for the approximations Eqs.(18),(19) are met. Taking the data of Ref.[37] for the collision broadening of sodium D lines by helium, we estimate the collision halfwidth as $\Gamma_{21} \simeq 5 \times 10^{10}\,{\rm s}^{-1}$, which exceeds the measured Doppler halfwidth of this transition $\Delta\omega_{\rm D}/2 = 4.7 \times 10^9\,{\rm s}^{-1}$ ($\Delta\nu_{\rm D}/2 = 0.75\,{\rm GHz}$). So we can neglect inhomogeneous broadening of the transition.

For the conditions under consideration we estimate $æ' \simeq 5 \times 10^{-9} I$ (where $I$ is in ${\rm W/cm}^2$), $|g|^2/\Gamma_{21}\Gamma_{32} \simeq |g|^2/\Gamma_{31}\Gamma_{32} \simeq æ'\Gamma_2/3\Gamma_{32}$. For the laser power 0.1 W focused to a spot $A = 10^{-5}\,{\rm cm}^2$ (confocal parameter $b \simeq 1\,{\rm cm}$) we obtain $|g| \simeq 3.6\,{\rm GHz}$, $æ' \simeq 5 \times 10^2$, $|g|^2/\Gamma_{21}\Gamma_{32} \simeq 0.1$. These magnitudes are about optimal ones and correspond to the estimated values, required to vary population difference at the probe transition $r_1 - r_3$ around zero. The estimated intensity $(1 - 10)\,{\rm kW/cm}^2$, required to achieve appreciated change of the line shape under the conditions considered, compares well with the experimental data obtained for the significant change of the ratio of population differences at the coupled transitions under similar conditions.[34]

The magnitude of AWI at $r_1 - r_3 = 0$ is estimated as $\alpha_{\rm p}(0)/\alpha_{\rm p0} \simeq \Gamma_2/3\Gamma_{32}$. Assuming $\Gamma_{32} \simeq w_{23}$, it may yield about 0.3% of the absorption in the absence of the strong field. It is seen that this quantity is very sensitive to the decay rate of the coherence at the Raman-like transition $|3\rangle$–$|2\rangle$.

## IV. NUMERICAL ANALYSIS OF POWER AND COLLISION INDUCED AWI AT THE TRANSITION BETWEEN DEGENERATE LEVELS OF ALKALIES

We shall consider such frequency detunings and collision broadening of the transitions, that hyperfine splitting of the levels can be neglected. However, account for degeneration of the levels may occur important for the quantitative analysis of the optimum conditions for AWI.

Assume that both driving and probe fields are linear and polarized in the same way. Then we assume that collisions can transfer only populations but not coherence. By that we can consider Eq.(5) for off-diagonal elements of density matrix as referred to the transitions between the same Zeeman sublevels of the upper and lower energy levels, which are not coupled. Unlike that equations for populations of the sublevels are coupled by the collisions. We assume that collisions are so strong, that populations of all sublevels within a same level are equal. Consequently we shall consider populations of any sublevel $r_{iM}$ and of the level $R_i$ to be related as $r_{iM} = R_i/g_i$, where $g_i$ is the degenerating factor of the level. Equations for the populations take the form

$$R_2 = (\frac{g_2}{g_1}R_1 - R_2)æ + R_3\frac{w_{32}}{\Gamma_2};$$

$$R_3 = R_2\frac{w_{23}}{\Gamma_3};\; R_1 + R_2 + R_3 = 1, \quad (21)$$

where æ is given by Eq.(17). The solution of (21) is

$$R_2 = \frac{g_2/g_1}{1+(g_2/g_1)[1+(w_{23}/\Gamma_3)]}\frac{æ'}{1+æ'};\ R_3 = R_2\frac{w_{23}}{\Gamma_3};$$

$$R_1 = \left[1+\frac{æ'}{1+(g_2/g_1)[1+(w_{23}/\Gamma_3)]}\right]\frac{1}{1+æ'}, \tag{22}$$

$$\frac{R_1}{g_1}-\frac{R_2}{g_2} = \frac{1}{g_1}\frac{1}{1+æ'}, \tag{23}$$

$$\frac{R_1}{g_1}-\frac{R_3}{g_3} = \frac{1}{g_1}\left\{1+\frac{[1-(g_2w_{23}/g_3\Gamma_3)]æ'}{1+(g_2/g_1)[1+(w_{23}/\Gamma_3)]}\right\}\frac{1}{1+æ'}. \tag{24}$$

It is seen from Eq.(24) that population inversion at the probe transition is impossible until buffer gas number density $N_b$ meets the requirement

$$N_b < v > (g_2\sigma_{23} - g_3\sigma_{32}) < g_3A_{31}. \tag{25}$$

Here $< v >$ and $\sigma_{ij}$ are the averaged relative collision velocity and fine structure population transfer cross-sections with the buffer atom, respectively.

For numerical analysis we use data presented in Table 1 (with He as buffer gas).

**Table 1.** Collision cross-sections.

| Atom | $(\sigma_{P_{3/2}-P_{1/2}})$/nm$^2$ | $(\sigma_{P_{1/2}-P_{3/2}})$/nm$^2$ | $(\sigma_{S_{1/2}-P_{3/2}})$/nm$^2$ | $(\sigma_{S_{1/2}-P_{1/2}})$/nm$^2$ |
|---|---|---|---|---|
| Na | 0.411[40] | 0.77[39] | 1.59[38] | 1.37[38] |
| K | 0.528[40] | 0.84[39] | 1.33[38] | 1.00[38] |
| Rb | 0.012[40] | 0.001[39] | 1.45[38] | 1.45[38] |

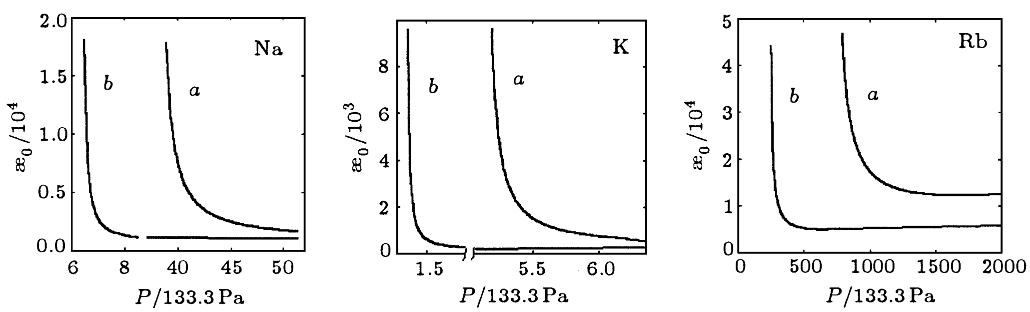


**Fig.2.** Dependence of threshold value of the saturation parameter $æ_0$, required for population inversion to be achieved, on the buffer gas pressure $a$. Dependence of threshold value of the saturation parameter $æ_0$, required in order to achieve inversion of sign of $\alpha_\mathrm{p}$ (AWI), on the buffer gas pressure $b$. Both dependencies are drown for monokinetic atoms at $v=0$ and at $\delta=\delta_\mathrm{p}=0$. $æ_0$ is resonant value for saturation parameter at collisionless limit ($æ_0 = 4|g|^2/A_{21}^2$).

Figure 2 (curves $a$) shows the dependence of the threshold value of the saturation parameter $æ_0$, required for population inversion, on the buffer gas pressure above this limit (equation $(R_1/g_1)-(R_3/g_3)=0$). Curves $b$ show the dependence of the threshold value of the saturation parameter $æ_0$, required in order to achieve inversion of sign of $\alpha_\mathrm{p}$ (AWI), on the buffer gas pressure (equation $[(R_1/g_1)-(R_3/g_3)]-[(R_1/g_1)-(R_2/g_2)]S=0$). Both curves are drawn for monokinetic atoms at $v=0$ and at $\delta=\delta_\mathrm{p}=0$. $æ_0$ is the resonant value for the saturation parameter at collisionless limit ($æ_0 = 4|g|^2/A_{21}^2$). In the range between curves $a$ and $b$ takes place changing sign of $\alpha_\mathrm{p}$ without changing of sign of population difference $(R_1/g_1)-(R_3/g_3)$. The minimum value of the saturation parameter $æ_0$, required in order to achieve AWI is $æ_0 = 92$ ($P_b \simeq 3.1\times 133.3$ Pa), $æ_0 = 848$ ($P_b \simeq 12.4\times 133.3$ Pa) and $æ_0 = 4971$ ($P_b \simeq 640.5\times 133.3$ Pa) for K, Na and Rb, respectively. Such values of the saturation parameter lead to considerable change of level populations which becomes $R_1 = 0.28$, $R_2 = 0.5$, $R_3 = 0.22$ for K, $R_1 = 0.264$, $R_2 = 0.51$, $R_3 = 0.226$ for Na and $R_1 = 0.324$, $R_2 = 0.462$, $R_3 = 0.214$ for Rb.

One can manipulate by the shape of the absorption/gain spectral line, position and bandwidth of the absorption and gain frequency-intervals. Analysis is given in Ref.[1]. Line shape is quite sensitive to the intensity and frequency detunings of the strong field from the resonance. Bandwidth of the gain grows and the maximum value decreases with the increase of the intensity of the strong field above a certain magnitude. Saturation of the population difference at the strong field transition and splitting of the common energy level oppose AWI effect, so that it can be optimize by proper choice of intensity and detunings of the strong field. In the case under consideration the inelastic collision frequency is an important parameter to be optimized as well.

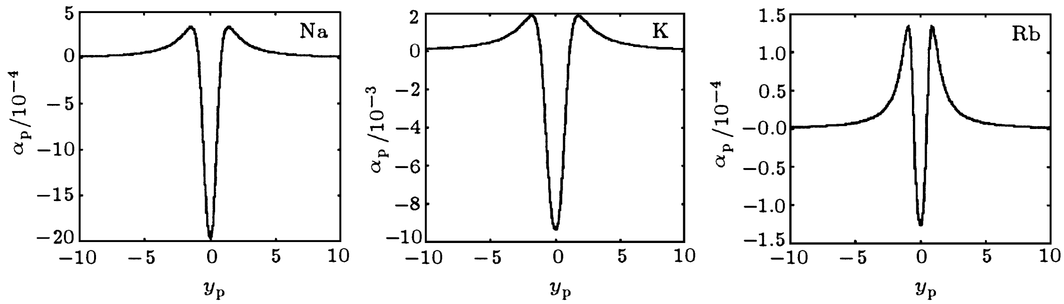


**Fig.3.** Line shape of normalized absorption (positive)/gain(negative) index $\alpha_p(\delta_p)$ of the probe field at the $D_1$ line in the presence of a strong laser field, resonant to the $D_2$ line. Abscise: Detuning of the probe laser in units of collision-broadened line halfwidth $\delta_p/\Gamma_{31}$. Ordinate: Indices in units of maxima of the corresponding values in the absence of the strong field. Strong field in exact resonance. Curves correspond to near zero population difference at the probe transition, so that line shapes are almost completely determined by the NIEF. Intensity of the strong field is such that Rabi frequency $g = 2.9 \times 10^9\,\mathrm{s}^{-1}$ (Na), $g = 0.37 \times 10^9\,\mathrm{s}^{-1}$ (K) and $g = 2.2 \times 10^9\,\mathrm{s}^{-1}$ (Rb) so that population difference at the probe transition $|1\rangle$–$|3\rangle$ is positive.

Figure 3 demonstrates the dependence of absorption/gain of probe field at frequency $\omega_p$ vs scaled detuning $y_p = \delta_p/\Gamma_{31}$ ($\delta = 0$) under optimal values $\alpha_p = 0.002$ for Na ($æ_0 = 8700,\ P = 170 \times 133.3\,\mathrm{Pa}$); $\alpha_p = 0.01$ for K ($æ_0 = 370,\ P = 16 \times 133.3\,\mathrm{Pa}$) and $\alpha_p = 1.3 \times 10^{-4}$ for Rb ($æ_0 = 12300,\ P = 1800 \times 133.3\,\mathrm{Pa}$). $(R_1/g_1) - (R_3/g_3)$ has values $2 \times 10^{-5}$, $3 \times 10^{-4}$ and $1.2 \times 10^{-4}$.

Taking the data of Ref.[39] for the collision broadening of D lines by helium, we estimate collision halfwidth as $\Gamma_{21} \simeq 8.8 \times 10^9\,\mathrm{s}^{-1}$, $\Gamma_{21} \simeq 0.73 \times 10^9\,\mathrm{s}^{-1}$ and $\Gamma_{21} \simeq 79.8 \times 10^9\,\mathrm{s}^{-1}$ for Na, K and Rb, respectively, which exceeds measured Doppler halfwidth of this transition for Na ($\Delta\omega_D/2 = 5.6 \times 10^9\,\mathrm{s}^{-1}$) and Rb ($\Delta\omega_D/2 = 2.15 \times 10^9\,\mathrm{s}^{-1}$). So in this case we can neglect inhomogeneous broadening of the transition. But in the case of K, $\Gamma_{21} \ll \Delta\omega_D/2 = 3.1 \times 10^9$ and it is necessary to perform averaging over velocities of atoms.

Figure 4 shows velocity-averaged absorption indices (for K) at inhomogeneously broadened $|1\rangle$–$|3\rangle$ transition in the presence of strong field at $|1\rangle$–$|2\rangle$ transition ($a - æ_0 = 3400$, $\delta = 0$, $b - æ_0 = 6 \times 10^4$, $\delta = 3\Delta\omega_D/2$).

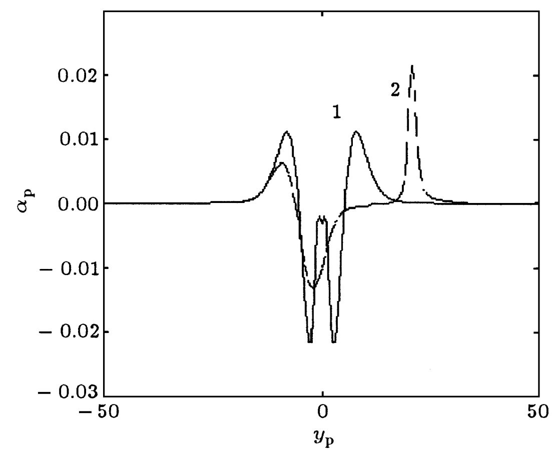


**Fig.4.**

In summary, this work shows a model of interference and collision driven V-type three degenerate-level system which provides gain without population inversion and resonance-enhanced refraction at vanishing absorption. Explicit formulas for analyzing the optimal conditions are presented. Comparative analysis of use of various alkalies relative to potential experiment is qualitatively discussed in details. Coherence destroying collision decrease the AWI and AWI effects compared to that in atomic beams. However the decrease may be comparable to that due to the Doppler broadening in metal vapors. The advantages are simplicity of the experiment, feasibility to manipulate by the population differences at the coupled transitions and to avoid some side effects. These make the experiment conformable to the simple commonly accepted

## REFERENCES


[1] T. Ya. Popova, A. K. Popov, *Zh. Prikl. Spektr.* (*USSR*), **12**(1970), 989 (Engl.: *J. Appl. Spectr.*, (1973), 734); *Izv. VUZ. Fiz.* (*USSR*), (11)(1970), 38 (Engl.: *Soviet Phys. J.* (1973), 1435); A. K. Popov. Vvedeniye v Nelineinuyu Spektroskopiyu (Introduction to Nonlinear Spectroscopy) (Novosibirsk, Nauka, 1983)(in Russ.).

[2] T. Ya. Popova *et al., ZhETF*, **57**(1969), 850 (*Sov. Phys. JETP*, **30**(1970), 466).

[3] For the Survey of Early Publications of Russian Groups on AWI see for Example a) S. G. Rautian and I. I. Sobelman, *Zh. Eksp. Teor. Fiz.*, **41**(1961), 456; b) D. N. Klyshko, Yu. S. Konstantinov, V. S. Tumanov, *Izv. Vuz. Radiofiz.*, **8**(1965), 513; c) A. M. Bonch-Bruevich, S. G. Przhibelskii, N. A. Chigir, *Vestnik MGU, Fisika*, **33**(1978), 35 (Engl.:p.28.); d) I. S. Zelikovich, S. A. Pulkin, L. S. Gaida, V. N. Komar, *Zh. Eksp. Teor. Fiz.*, **94**(1988), 76; e) S. G. Rautian and A. M. Shalagin, Kinetic Problems of Nonlinear Spectroscopy (North Holland, 1991).

[4] O. Kocharovskaya, Y. L. Khanin, *JETP Lett.*, **48**(1988), 630.

[5] M. O. Scully *et al., Phys. Rev. Lett.*, **62**(1989), 2813.

[6] S. E. Harris, *Phys. Rev. Lett.*, **62**(1989), 1022.

[7] L. M. Narducci *et al., Opt. Commun.*, **81**(1991), 379.

[8] O. Kocharovskaya, *Phys. Rep.*, **219**(1992), 175.

[9] M. O. Scully, *Phys. Rep.*, **219**(1992), 191.

[10] M. Fleischhauer *et al., Phys. Rev.*, **A46**(1992), 1468.

[11] J. Y. Gao *et al., Opt. Commun.*, **93**(1992), 93.

[12] A. K. Popov and B. Wellegehausen, Interference and CW Gain without Population Inversion in Three-Level Systems: In Scientific Program of Euroconference on LICS and Related Topics (Crete, Greece, May, 1993).

[13] Th. Müller-Wirts, H. Eichmann, A. K. Popov and B. Wellegehausen, Gain without Population Inversion at Homogeneously Broadened $D_1$ Line of Sodium.- In Proc. EQEC'93 (Florence, Italy, Sept. 1993), pp.23, 318.

[14] Th. Müller-Wirts, B. Wellegehausen and A. K. Popov, Experiments on Na Vapors, Related to Lasing with (out) Inversion.- In Scientific Program of Crested Butte Workshop on Effects of Atomic Coherence and Interference (The Woodlands, Texas, U. S. A., 1993).

[15] U. Rathe *et al.*, **A47**(1993), 4994.

[16] A. Nottelman *et al., Phys. Rev. Lett.*, **70**(1993), 1783.

[17] W. E. Van der Veer *et al., Phys. Rev. Lett.*, **70**(1993), 3243.

[18] E. Fry *et al., Phys. Rev. Lett.*, **70**(1993), 3225.

[19] A. K. Popov, V. G. Arkhipkin, Th. Müller-Wirts and B. Wellegehausen, Interference Processes and Gain without Inversion in Three Level Schemes, Paper QThA2.- In Proc. CLEO/IQEC'94 (Anaheim, CA, USA, May, 1994); V. G. Arkhipkin, A. K. Popov, B. Wellegehausen, Th. Müller-Wirts, Interference Processes and Gain without Inversion in Three Level Systems.- IQEC'94 (USA, 8-13, May, 1994), p.105.

[20] Th. Müller-Wirts, M. Dernier, A. K. Popov and B. Wellegehausen, Paper QMG7-In Proceed. CLEO/Europe EQEC (Amsterdam, 1994).

[21] J. A. Kleinfeld, A. D. Streater, *Phys. Rev.*, **A49**(1994), R4301.

[22] J. Y. Gao *et al., Opt. Commun.*, **110**(1994), 590.

[23] M. Xiao *et al., Phys. Rev. Lett.*, **74**(1995), 666.

[24] A. S. Zibrov *et al., Phys. Rev. Lett.*, **75**(1995), 1499.

[25] A. K. Popov, *Izvestija of Akademii Nauk* (*in Russ.*), **60**(6)(1996), 99 [Engl.: *Bull. Russ Acad. Sci.* (*Ser. Phys.*)].

[26] A. K. Popov, S. G. Rautian, *Proc. SPIE*, **2798**(1996), 49.

[27] A. K. Popov, *Proc. SPIE*, **2798**(1996), 231.

[28] A. K. Popov and B. Wellegehausen, *Laser Physics* (*Moscow*), **6**(1996), 364.

[29] H. Y. Ling, Y. Q. Li, M. Xiao, *Phys. Rev.*, **A53**(1996), 1014.

[30] H. Z. Zhang, J. Y. Gao, *Z. Phys.*, **D38**(1996), 5.

[31] A. S. Zibrov *et al., Phys. Rev. Lett.*, **76**(1996), 3935.

[32] O. Schmidt *et al., Phys. Rev.*, **A53**(1996), R27.

[33] B. A. Glushko *et al., Opt. i Spektrosk.* (*USSR*), **54**(1982), 762 [Engl.: *Opt. Spectrosc.*, **54**(4)(1982)].

[34] S. N. Atutov *et al., Opt. i Spektrosk.* (*USSR*), **56**(1984), 215 (Engl.: *Opt. Spectrosc.*, **56**(1984), 134.)

[35] Yu. I. Heller and A. K. Popov, Laser Induction of Nonlinear Resonances in Continuous Spectra (Novosibirsk, Nauka, 1981)(in Russ.) [Engl. Transl.: *J. Sov. Laser Research*, **6**(1–2)(Jan.- Feb. 1985), Plenum, c/b Consultants Bureau, New York, USA].

[36] J. A. Jordan, P. A. Franken, *Phys. Rev.*, **142**(1966), 20.

[37] J. F. Kielkopf, *J. Phys.*, **B13**(1980), 3813.

[38] E. L. Lewis, *Phys. Rep.*, **58**(1980), 1.

[39] T. J. Beahn *et al., Phys. Rev.*, **141**(1966), 83.