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FOREIGN TECHNOLOGY DIVISION

AIR FORCE SYSTEMS COMMAND

FLOWING EFFECTS IN GAS LASERS

by

Gao Zhi

FOREIGN TECHNOLOGY DIVISION

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FLOWING EFFECTS IN GAS LASERS

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Abstract

Currently accepted theory (e.g. see [1-3]) states that saturation intensity and gain (or optical power density) increase without limit with the increase of the flow speed. These conclusions are not true. We have shown instead that they tend to be limiting values with the increase of flow speed. The variations of the parameters mentioned above with flow speed are presented.

All of the writings [1-3] and references [4,5] on the flowing effects in gas lasers use the clear and succinct qualitative theory brought forth by Demaria [6,7]. In Demaria's analysis [6,7], the saturation intensity gain and laser power density increase without limit with the increase of the flow speed. These conclusions appear to be worth investigating in regard to the often brought forth doubts by these people. Below we present a more rational and clear analysis so as to clarify and answer this question.

The analysis begins from the speed equations. For purposes of conciseness, we assume that the changes of gas flow parameters p, T and u can be neglected, the laser propagation direction and flow direction (i.e. the x direction) are perpendicular to eachother, the loss (including transmission, absorption etc. losses) is not related to x and the pumping speed is a constant. As regards the energy level system shown in Fig. 1, the particle number variation equations of the laser's upper energy level and lower energy level are:

$$\frac{\partial N_2}{\partial t} + u\frac{\partial N_2}{\partial x} = R_2 - \frac{N_2}{\tau_2} - (N_2 - N_1)\frac{\sigma I}{h\nu}$$

$$\frac{\partial N_1}{\partial t} + u\frac{\partial N_1}{\partial x} = R_1 - \frac{N_1}{\tau_1} + (N_2 - N_1)\frac{\sigma I}{h\nu} \qquad (1)$$

In the formulas, t is the time, u is the flow speed, N_2 and N_1 are the upper and lower energy level particle numbers, R_2 and R_1 are the volume pumping rates of the upper and lower energy levels, τ_2 and τ_1 are the upper and lower energy level collision deactivation characteristic times, σ and I are separately the excited emission section and ratiation intensity, and hv is the light quantum energy.

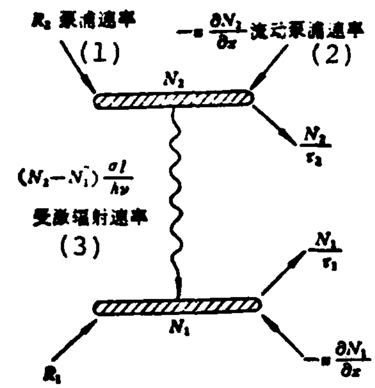

Fig. 1 The two energy level systems and speed equations.
Key: (1) Pumping rate; (2) Flow pumping rate; (3) Excited radiation speed.

As regards the steady-state emission unrelated to time t, the gain is equal to the loss. By using the condition of the loss being nearly unrelated to x in the gas flow laser, we can find the following solutions to the set of equations in (1):

$$N_2 + N_1 = (N_2^0 + N_1^0)\exp\left(-\frac{\tau_2+\tau_1}{2\tau_1\tau_2}\tau_f\right)$$
$$+ \frac{2\tau_1\tau_2(R_2+R_1)}{\tau_2+\tau_1}\left[1-\exp\left(-\frac{\tau_2+\tau_1}{2\tau_1\tau_2}\tau_f\right)\right]$$
$$+ \frac{(\tau_2-\tau_1)\alpha}{(\tau_2+\tau_1)\sigma}\left[1-\exp\left(-\frac{\tau_2+\tau_1}{2\tau_1\tau_2}\tau_f\right)\right] \quad (2)$$
$$\alpha = \sigma(N_2 - N_1) = \frac{\alpha_0}{1 + I/I_s} \quad (3)$$

In the formulas

$$\alpha_0 I_s = \frac{h\nu}{2}\left\{(R_2 - R_1) + \frac{(\tau_2-\tau_1)(N_2^0+N_1^0)}{2\tau_1\tau_2}\exp\left(-\frac{\tau_2+\tau_1}{2\tau_1\tau_2}\tau_f\right)\right.$$
$$\left.+ \frac{(\tau_2-\tau_1)(R_2+R_1)}{(\tau_2+\tau_1)}\left[1-\exp\left(-\frac{\tau_2+\tau_1}{2\tau_1\tau_2}\tau_f\right)\right]\right\} \quad (4)$$
$$I_s = \frac{h\nu}{2\sigma}\left\{\frac{\tau_2+\tau_1}{2\tau_1\tau_2} - \frac{(\tau_2-\tau_1)^2}{2\tau_1\tau_2(\tau_2+\tau_1)}\left[1-\exp\left(-\frac{\tau_2+\tau_1}{2\tau_1\tau_2}\tau_f\right)\right]\right\} \quad (5)$$

$\tau_j = \frac{X}{u}$ is the transit time of the gas flow passing through the laser emission area in the optical cavity, a_o is the small-signal gain coefficient when $I \approx 0$ and l_s is the saturation intensity. The upper symbol o indicates the gas flow conditions of the initial position of the laser emission. When there is a low flow speed, $\tau_f \gg \tau_2, \tau_1$, and therefore

$$\alpha \approx \frac{\sigma(R_2\tau_2 - R_1\tau_1)}{1 + \frac{\sigma I}{h\nu}(\tau_2+\tau_1)} \quad (3)_1$$
$$\alpha_0 I_s \approx \frac{h\nu(R_2\tau_2 - R_1\tau_1)}{\tau_2+\tau_1} \quad (4)_1$$
$$I_s \approx \frac{h\nu}{\sigma(\tau_2+\tau_1)} \quad (5)_1$$

As regards high speed flow limit $\tau_f \ll \tau_2, \tau_1$, we therefore have

$$\alpha \approx \frac{\sigma\left[\frac{2\tau_1\tau_2}{\tau_2+\tau_1}(R_2-R_1)+\frac{\tau_2-\tau_1}{\tau_2+\tau_1}\Delta N^\circ\right]}{1+\frac{4\tau_1\tau_2\sigma}{h\nu(\tau_2+\tau_1)}I} \qquad (3)_2$$

$$\alpha_0 I_s \approx \frac{h\nu}{2}\left(R_2-R_1+\frac{\tau_2-\tau_1}{2\tau_1\tau_2}\Delta N^\circ\right) \qquad (4)_2$$

$$I_s \approx \frac{h\nu(\tau_2+\tau_1)}{4\tau_1\tau_2\sigma} \qquad (5)_2$$

The initial position of the laser emission usually satisfies $N_2^\circ \gg N_1^\circ$ and therefore acts as the rational approximation of $N_2^\circ+N_1^\circ \approx N_2^\circ \approx N_2^\circ-N_1^\circ=\Delta N^\circ$. As regards the gas dynamic laser, there is no pumping in the optical cavity, that is $R_2 \equiv R_1 \equiv 0$, the pumping is carried out in the optical cavity's upstream high pressure gas storage chamber and the reverse of the distribution of the energy level particle number is obtained in a fast expanding unbalanced flow. Therefore, it is only necessary to let $R_2 \equiv R_1 \equiv 0$ in formulas $(3)_2$ and $(4)_2$ to be able to obtain the gain of the gas dynamic laser's high speed flow limit as well as the theoretical expression of the laser's power density.

Because $\tau_2 \gg \tau_1$, relational formulas (3)-(5) can also be slightly simplified. When there is a low flow speed, the results of relational formulas $(3)_1$-$(5)_1$ are completely identical with those of [6,7]; the limited relational formulas $(3)_2$-$(5)_2$ when there is high flow speed are then completely different from Demaria's results [6,7]. In the high flow speed relational formulas of References [6,7], saturation intensity I_s, optical power density a_oI_s or gain a are all inverse ratios to τ_f, that is, they increase without limit with the increase of the flow speed. Relational formulas $(3)_2$-$(5)_2$ then show that the high flow speed limits of I_s, a_oI_s or gain a are all finite values and these limit values do not have any noticeable relation to τ_f or flow speed u. The limit value of I_s which increases with the flow speed is $\frac{h\nu}{4\tau_1\sigma}$; the limit value of relative gain $\frac{al}{hv}$ or optical power density $\frac{a_o I_s}{hv}$ which changes with the increase of the flow speed is $\left(\frac{R_2-R_1}{2}+\frac{\Delta N^\circ}{4\tau_1}\right)$. $\frac{\Delta N^\circ}{4\tau_1}$ indicates the contribution produced by the particle number reverse storage in the optical cavity's upstream overtaking flow. This contribution is in direct ratio with ΔN°, in inverse ratio with τ_1 and therefore forms a ratio with the quadratic equation of the gas pressure.

By comparing formulas $(3)_1$-$(5)_1$ with formulas $(3)_2$-$(5)_2$, we can see that when compared to situations without flow, the flow causes the limit multiple of the I_s increase to be $\frac{\tau_2}{4\tau_1}$. That is, the increased limit multiple is only related to the specific value of the upper and lower energy level collision deactivation characteristic times; the flow causes the optical power density or gain increased limit multiple to be about $\frac{\Delta N^\circ}{4\tau_1 R_2}$. Using the continuous wave CO_2 gas laser as an example [8,9], R_2 is about 10^{14}-10^{16} particles/second·cm^3 and ΔN° is about 10^{15}-10^{17} particles/cm^3. Therefore, the flow can cause the laser power density or gain to increase several quantitative levels and cause the increase of I_s to be less than one quantitative level. Figures 2 and 3 give the relational curves of I_s and $\frac{a_o I_s}{hv}$ or relative gain $\frac{al}{hv}$ which changes with transit time τ_f. The curve is clearly divided into three different characteristic areas and in the slow flow speed area, I_s, $\frac{a_o I_s}{hv}$ or $\frac{al}{hv}$ are all constants; in the medium flow speed area, these performance parameters monotonically rise with the increase of the flow speed; in the high flow speed area, these performance parameters tend towards their own limit value and the limit values are all constants with no noticeable relation to the flow speed. It should be specially pointed out that when using the flow effect to raise the laser power output, the size of the required flow speed should cause transit time τ_f to be in the τ_1 to $10\tau_1$ range; aside from this, the flow speed required to raise the laser power density or gain must be about ten times smaller than the flow speed required to raise the saturation intensity.

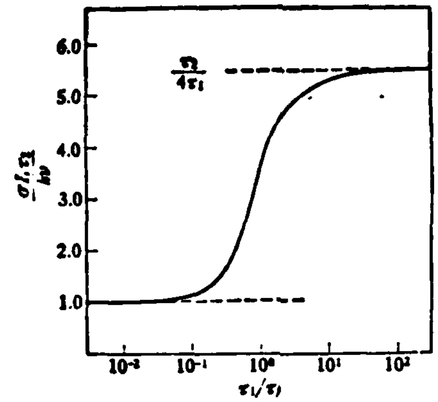

Fig. 2 Relationship of the saturation intensity and transit time τ_f.

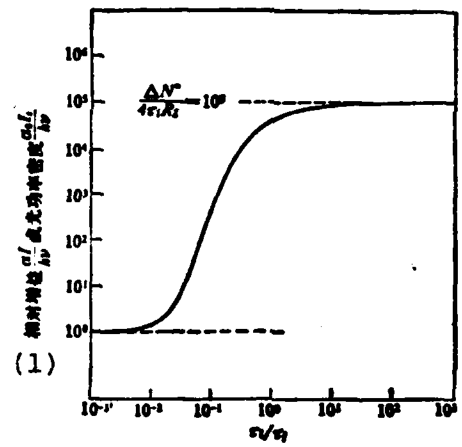

Fig. 3 Relationship of the gain and optical power density with transit time τ_f.
Key: (1) Relative gain $\frac{al}{hv}$ or optical power density $\frac{a_o I_s}{hv}$.

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