HYSTERESIS PHENOMENA IN A CO_2 LASER WITH A NONLINEAR ABSORBER

V.V. Dembovetskii

Scientific-Research Center for Technological Lasers of the Academy of Sciences of the USSR, Troitsk
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Hysteresis phenomena in a CO_2-laser with a nonlinear intracavity absorber were studied for the lasing lines P(16)–P(28) in the 10 μm transition. Sulphur hexafluoride was used as the nonlinear absorber. The current and frequency hysteresis as well as the hysteresis accompanying a change in the unsaturated absorption and the Q-factor of the resonator were recorded experimentally. The possibility of using such a laser as a fast "gas shutter" is discussed.

The existence of hysteresis effects in the output characteristics of laser radiation was first demonstrated experimentally in Ref. 1 for a He–Ne laser with nonlinear absorption. A theoretical explanation of these effects, based on the nonmonotonic dependence of the effective gain of the laser (taking absorption into account) on the amplitude of the electric field, is given in Ref. 2, where a criterion for the appearance of hysteresis phenomena is presented. In studying hysteresis phenomena in lasers with nonlinear absorption several types of hysteresis effects are distinguished: 1) current hysteresis accompanying a change in the discharge current, i. e., a change in the intensity of pumping of the active medium; 2) absorption hysteresis accompanying a change in the unsaturated absorption (for example, a change in the pressure of the absorbing gas); 3) frequency hysteresis – accompanying a change in the cavity frequency (a change in the cavity length); 4) hysteresis accompanying a change in the cavity Q-factor (for example, the introduction of nonresonant losses). For a long time it was difficult to observe experimentally hysteresis effects in a CO_2 laser with nonlinear absorption (for passive systems such lack of single-validness between the input and output signal became known later as optical bistability) because of the appearance of passive Q-switching, which, as a rule, arose before the criterion for the appearance of hysteresis was satisfied. The passive Q-switching regime was first observed in a CO_2 laser using SF_6 as the nonlinear absorber.[3]

The appearance and characteristics of the hysteresis curves can be understood starting from a simple model of a laser with nonlinear absorption.[4] In this case the intensity in the cavity (proportional to the output power of the laser) is described by the simple relation

$$\frac{\eta_1}{1+\beta_1\varepsilon^2} - \frac{\eta_2}{1+\beta_2\varepsilon^2} - 1 = 0, \tag{1}$$

where η_1 and η_2 are the unsaturated gain and absorption, normalized to the cavity losses; ε^2 is the squared amplitude of the electric field; and, β_1 and β_2 are the saturation parameters of the active and absorbing media. The relation (1) is valid for homogeneously broadened lines of absorbing and amplifying media and when the centers of the gain and absorption lines coincide with the cavity frequency. The magnitude of the field is given, by the following expression:

$$\varepsilon^2 = \Big\{\beta_2(\eta_1 - 1) - \beta_1(\eta_2 + 1) \pm \sqrt{\left[\beta_2(\eta_1 - 1) - \beta_1(\eta_2 + 1)\right]^2 + 4\beta_1\beta_2(\eta_1 - \eta_2 - 1}\Big\}/(2\beta_1\beta_2) \tag{2}$$

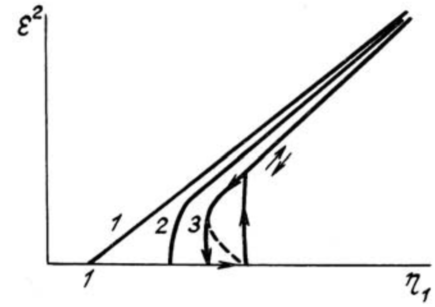

FIG. 1. The output power of a laser with nonlinear absorption versus the gain in the active part.

Figure 1 shows the characteristic dependences of the intensity, calculated using the formula (2), for three characteristic cases: 1) $1 - \eta_2 = 0$; 2) $\eta \le \eta^{cr}$ (where $\eta^{cr} = \dfrac{\beta_2}{\beta_2 - \beta_1}$ is the critical value of the absorption; for $\eta_2 > \eta_2^{cr}$ hysteresis is possible, see the criterion for the appearance of hysteresis in Ref. 2; 3) $\eta_2 > \eta_2^{cr}$. For all three cases $\beta_2\varepsilon^2 \gg \beta_1\varepsilon^2 \geq 1$. Thus the existence of two different real roots of Eq. (1) determines the existence of hysteresis. In this case the dependence of the absorption coefficient on the intensity can be quite complicated. For example, for the lasing lines of the CO_2 laser 10P(12)–10P(28) the saturated absorption coefficient is described by the expression (3) (Refs. 5 and 6):

$$\alpha_{eff} = \frac{\alpha_0}{1 + I/I_s} + \frac{\beta_0 I/I_s}{1 + I/I_s}, \tag{3}$$

where α_0 and β_0 are the unsaturated absorption ray coefficients of the modes ν_3 and $\nu_3 + \nu_6$ of SF_6, and I_s is the saturation intensity; α_0, β_0 and I_s, are different for different lines. When the CO_2 laser is tuned from one lasing line to another it is possible to obtain hysteresis effects as well as a transition into the passive *Q*-switching regime (for constant absorption and level of pumping of the active medium), depending on which criterion is satisfied: the criterion for the appearance of hysteresis or the criterion for the self-*Q*-switching regime.[4] Hysteresis effects have now also been obtained in lasers based on other active substances, for example, in an N_2O laser.[7]

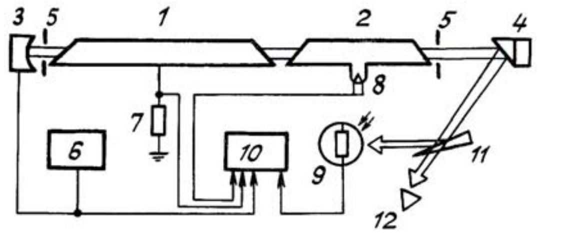

FIG. 2. Block diagram of the experimental arrangement: 1) discharge tube; 2) absorption cell; 3) spherical mirror; 4) diffraction grating (100 lines/mm); 5) iris diaphragm; 6) low-frequency sawtooth-voltage generator; 7) measuring resistance in the cathode circuit; 8) manometric thermocouple transducer; 9) photodetector; 10) plotter; 11) ZnSe wedge; 12) power meter.

In this work the hysteresis effects in a CO_2 laser with nonlinear absorption were studied. Sulphur hexafluoride was used as the absorber. A block diagram of the experimental arrangement is presented in Fig. 2. The amplifying (active) part of the laser consists of two discharge gaps with separate high-voltage power sources. One discharge gap is ~ 1.3 m long. The absorption cell is ~ 0.65 m long. Two iris diaphragms were placed inside the resonator near the spherical mirror and the diffraction grating in order to single out the fundamental Gaussian mode. The hysteresis curves were recorded on an *X*–*Y* plotter; the signal from the photodetector (RTN-10g radiation compensated element) was fed to the *Y* input and a signal proportional to the discharge current or the change in the losses or the length of the cavity or the pressure of the absorbing gas was fed to *X* input. The cavity length was changed with the help of piezoelectric correctors, on which a spherical mirror and a diffraction grating were fastened. The voltage on the piezoelectric correctors was fed from a low-frequency sawtooth-voltage generator. The lasing line of the laser was intensified with the help of a SPM-2 monochronomator. The vacuum system made it possible to evacuate the cell to a level 10^{-5} torr, and the absorbing gas could be injected and pumped out either continuously or in small portions. In order to compare the hysteresis curves (Figs. 3–6) the measurements were performed everywhere on the same lasing line of the laser: 10P(16).

The presence of two types of hysteresis in Fig. 3 (to the left and right of the center of the lasing line) is connected with the fact that the absorption lines of SF_6 near the lasing line of the laser 10P(16) form an effective asymmetric absorption contour. The dependence of the output power without the absorbing gas in the cell is marked in Figs. 3–6 by the number 1. On all figures the change in the intensity in the forward and reverse passes are marked by arrows.

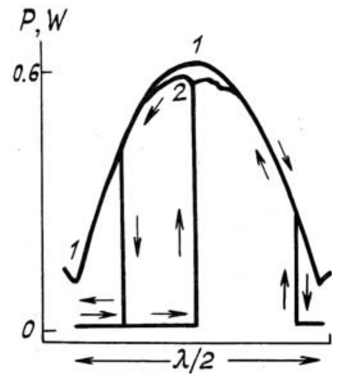

FIG. 3. Frequency hysteresis. The SF_6 pressure in the cell is equal to 8.5 mtorr.

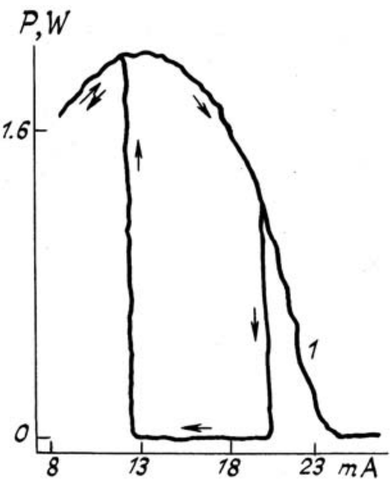

FIG. 4. Current hysteresis. The SF_6 pressure in the cell is equal to 14 mtorr.

The appearance of lasing at discharge currents less than the value corresponding to the maximum output power with current hysteresis (Fig. 4) can be explained as follows: the output power is proportional to the product of the saturated gain and the saturation intensity; the gain decreases monotonically; and, the saturation intensity is an increasing function for currents in the range 4–40 mA. Thus the value of the current for which maximum output power is observed does not correspond to the maximum value of the unsaturated gain; the appearance of lasing, however, is determined by condition $\eta_1 - \eta_2^{-1} = 0$ (Ref. 2). For absorption hysteresis it is interesting to note that as the gain increases (two discharge gaps are used instead of one, as in Fig. 5) the range of pressure hysteresis (and therefore absorption hysteresis) becomes wider and shifts toward higher absorption (for example, Fig. 4 in Ref. 8).

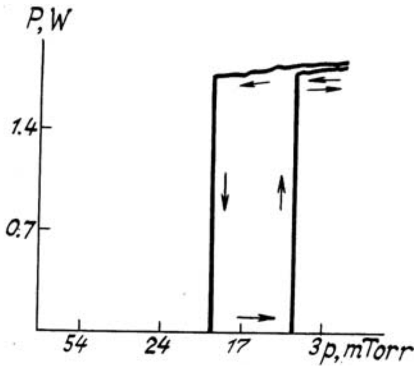

FIG. 5. Hysteresis as a function of the absorption (the gas pressure in the cell). $I_{\rm dis}$ = 15 mA.

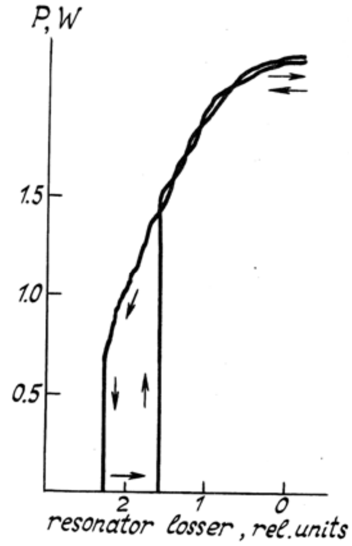

FIG. 6. Hysteresis as a function of the cavity losses. The SF_6 pressure in the cell is equal to 9 mtorr. $I_{\rm dis}$ = *16* mA.

The stability in the region of hysteresis was specially studied. When losses are introduced into the cavity in the region of hysteresis lasing stopped and did not reappear when the previous level of losses was restored. This picture corresponds to the curve of the effective gain versus the field with one maximum and two stationary points with zero and nonzero electric fields (curves 3–5 in Fig. 2 of Ref. 2), and in addition the unsaturated gain of the laser (with zero field) is less than the losses, which makes the nonlasing state stable.

An interesting effect was observed: lasing stopped in the stationary state and approach in the pulsating state. This regime was observed on the lasing lines of the $C0_2$ laser 10P(18)-10P(20) and for the same pressures passive Q-switching was observed on the lines 10P(24)-10P(28). In the first case the criterion for the appearance of lasing for the peak values of the pulse may already be satisfied, while for the rest of the pulse (the tail) it is not yet satisfied. We note that the stopping of lasing occurred smoothly. As far as we know this is the first observation of this effect.

From the viewpoint of applied problems, absorption hysteresis is, in our opinion, most interesting. It is possible to build a "gas shutter", for example, for technological lasers, based on this effect. In the lasing regime (as one can see from Fig. 5) such a shutter does not introduce any losses and therefore it does not reduce the output power. In the closed state, since there is no lasing, the question of removing heat from the shutter does not arise (though it does arise for shutters of the standard type). The actuation time of such a shutter is an order of magnitude shorter than that of the usually employed mechanical shutter.

In conclusion I thank G.I. Surdutovich for fruitful discussions regarding hysteresis phenomena in lasers.

REFERENCES

1. V.N. Lisitsyn and V.P. Chebotaev, Pis'ma Zh. Eksp. Teor. Fiz., **7**, No. 3 (1968).
2. A.P. Kazantsev, S.G. Rautian, and G.I. Surdutovich, Zh. Eksp. Teor. Fiz., 54, 1409 (1968).
3. O.R. Wood and S.E. Schwars, Appl. Phys. Lett. **11**, 88 (1967).
4. V.V. Dembovetskii and G.I. Surdutovich, *Laser Beams* (Khabarovsk, 1975).
5. E.F. Plinski and K.M. Abramski, Appl. Opt., **14**, 301 (1984).
6. H. Brunet, IEEE. T. **QE-6**, 678 (1970).
7. C.O. Weiss, Opt. Commn. **42**, 291 (1982).
8. V.V. Dembovetskii and G.I. Surdutovich, *Laser Beams* (Khabarovsk, 1985).