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# Method of double-stabilization of conventional $CO_2$ gas laser

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A conception of a system with two automatic control systems for a simultaneous frequency and output power stabilization of a conventional $CO_2$ gas laser has been analysed theoretically. Main theoretical conclusions have been checked experimentally. The system of a double-stabilization based on this conception ensures the frequency stability of order of $10^{-8}$ for the average time equal to 1 s and the output power stability about $\pm 0.2\%$ over 15 minute periods.

## 1. Introduction

A conventional $CO_2$ gas laser is an unstable source of radiation. Acoustic and mechanical vibrations of the laser structure, changes in the spacing of the laser mirrors due to thermal expansion, as well as the discharge noise are the main factors responsible for the unstable work of a $CO_2$ laser. They cause the instabilities of both the laser frequency and output power. Typically, in a conventional $CO_2$ gas laser, the frequency fluctuations range within $10^{-6}$–$10^{-7}$ [1] and instabilities of the output power can reach $\pm 10\%$ or more over 15 minute periods [2], [3].

In many applications of a $CO_2$ discharge laser, such as plasma diagnostics, atomic and molecular spectroscopy, metrology and precise optical measurements, a stabilized laser beam is required. A certain reduction of the output beam noise can be obtained by constructing a special laser setup [4], [5]. Considerable decrease of the laser beam instabilities can, however, be gained by using additional automatic control systems. These systems can stabilize either output beam power or radiation frequency. In some particular optical studies, e.g., in magnetooptical studies of semiconductors with narrow forbidden band, a $CO_2$ laser with high-stabilized output beam is needed. It means that such a laser must be equipped with two different, simultaneously working, automatic control systems: one for radiation frequency stabilization and second for output power stabilization.

In the recent paper [6], a laboratory model of a $CO_2$ gas laser with simultaneous frequency and output power stabilization has been described. Below, the problems connected with the equipment of a $CO_2$ gas laser with a double-stabilization system have been discussed. The possibility of a proper simultaneous operation of two different automatic control systems has been analysed qualitatively for the double-stabilization system proposed by us. Main final conclusions have been checked experimentally.

## 2. Conception of a double-stabilization system

### 2.1. Criteria of choice

Each double-stabilization system requires a suitable choice of both frequency and power stabilization systems. This choice depends first of all on the requirements with respect to relative frequency and output power instabilities. At the same time, it is important to know the time period during which these requirements should be maintained. The possibility of a proper simultaneous operation of both stabilization systems should be also taken into account.

Other elements which should be considered when making the choice are the following: number and kind of both optical and mechanical elements connected with given double-stabilization system, compactness of a $CO_2$ laser structure equipped with a given system, losses of output beam power due to switching-on both stabilization feedback loops and, the last criterion, costs connected with the equipment of a $CO_2$ gas laser with the chosen double-stabilization system.

The concept of a double-stabilization system worked out by us is based on the following requirements:

1. Relative frequency instability – $10^{-8}$.
2. Relative output beam power instability – below $\pm 0.3\%$.
3. Time period during which these output beam parameters should be maintained – 15 minutes.
4. Output power losses – the least possible.

### 2.2. Choice of frequency stabilization system

Many methods of laser frequency stabilization have been described in the literature [7]–[13], among them, the methods of frequency stabilization to the centre of the output power versus frequency curve which secure a relative stability of order of $10^{-8}$. Of different possible practical methods of the stabilization to the centre of the gain curve, we have chosen a system in which variations in the impedance of the laser plasma tube are used to produce the frequency correction [7], [9]. This method is very attractive because it requires neither a beam splitter nor an infrared detector. Thus, by using this method, additional output power losses can be avoided.

### 2.3. Choice of output power stabilization system

A few different power stabilization systems have been described in the literature [2], [3], [12], [14], [15]. They can be divided into two groups, i.e., external and internal output power stabilization systems. The first is based on a regulated optical attenuator [12] while the second one on an automatically controlled regulation of the discharge current in the laser tube [2], [3], [14], [15]. The last method is simple, it does not require additional optical elements and ensures low output power losses. In such a system the output power stability below $\pm 0.3\%$ can be achieved in over 20 minutes [3], [15]. That is why it was chosen for the double-stabilization system.

### 2.4. Block diagram of the double-stabilization system

Both the stabilization systems chosen by us define the requirements for certain details of the $CO_2$ gas laser to which these systems will be attached. These details depend first of all on the way in which both the systems are connected with a given $CO_2$ gas laser. The connection suggested by us, as one of a few possible, as well as necessary details of the $CO_2$ laser structure are shown in Fig. 1.

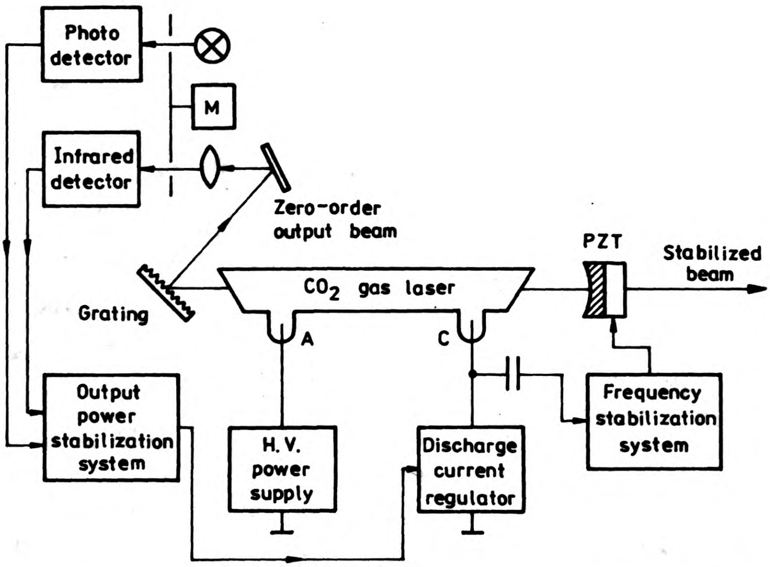


Fig. 1. Block diagram of the $CO_2$ gas laser system with a simultaneous stabilization of the radiation frequency and output power

A diffraction grating was used as one of the resonator mirrors for two reasons. Firstly, because then the $CO_2$ gas laser oscillates on only one $J$-value of transition, and this is very desirable for the frequency stabilization system. Secondly, the zero-order output beam of the grating can be used for power stabilization system. It means that the working beam may remain unsplitted and that the additional losses of the output power did not occur.

A diaphragm placed inside the laser cavity assures the suppression of non-axial modes. Thus, the $CO_2$ laser oscillates on single transverse mode. The phase-sensitive detection technique used in the power stabilization loop decreased the influence of the infrared detector noise on the output power stability.

## 3. Interaction of the stabilization loop

It is obvious that in such a system of a simultaneous stabilization of the output power and radiation frequency there may occur an interaction of both the feedback loops. The frequency stabilization method utilizes the variations of the impedance of the laser plasma tube with the optical output power. The frequency-error signal is equal to zero at the frequency corresponding to the peak of the gain profile. Correction signal different from zero occurs when an output power is changed under the influence of a random disturbance factor. This error signal causes the cavity resonance frequency to coincide with the peak of the laser gain profile. The influence of these disturbance factors, which not only change the output power in a random way but also the radiation frequency, on the output will be compensated by the frequency loop. In other words, the frequency loop will stabilize not only radiation frequency but, partially, the output power. Thus, the influence of the frequency loop on the output power is always advantageous.

The last conclusion is no more true for the reverse influence, i.e., that of the power stabilization loop on the frequency stability. The power loop is then switched-on so that each change of the output power exerts a change of the DC discharge current intensity. It brings about the change in the refractive index of the gas medium and consequently the laser frequency varies. An immediate influence of the power loop on the frequency loop does not occur, because the change of current causes the variation of the amplitude of the mapping gain profile in the tube impedance, its shape, however, remains the same.

Current-dependent shift in the frequency of a $CO_2$ conventional laser oscillations has been studied by MOCKER [16] and KOLOSOVSKII [17]. A $10^{-8}$ relative frequency change due to 1 mA change of the discharge current intensity has been confirmed in both the different experiments. The extent of laser frequency changes depends on the range of the discharge current changes. The last range depends on i) the extent of the output power instability, and ii) on the slope of the curve representing the output power versus the DC discharge current intensity. Thus, in order the influence of the power stabilization loop on a frequency stability be the least possible it is desirable to decrease the output power instabilities. This purpose may be achieved by a) special construction of the laser setup, b) using the discharge current stabilizer, and c) switching-on (as in our conception of the double-stabilization system) the frequency stabilization loop. By using these methods and optimizing the slope of the curve mentioned above it seems possible to achieve the conditions in which the influence of the power stabilization loop on the frequency stabilization loop can be neglected.

## 4. Experimental

An experiment was made in order to prove some theoretical conclusions presented in Sect. 3. In this experiment we have used a $CO_2$ gas laser described in details in [6]. Technical design of this laser setup with two feedback loops was based strictly on the block diagram presented in Fig. 1.

In order to check how the closing of the frequency stabilization loop influences the output power, the $CO_2$ laser output power fluctuations were measured under two different work conditions, i.e., without closing any stabilization loop, and when the frequency loop was closed. Typical strip chart recorder plots are shown in

Fig. 2. In conformity with our conclusion the closing of the frequency loop causes the decrease of the output power fluctuations, which in our case is twofold. The extent of the output power fluctuations at closed frequency stabilization loop equals about $\pm 1.8\%/15$ min.

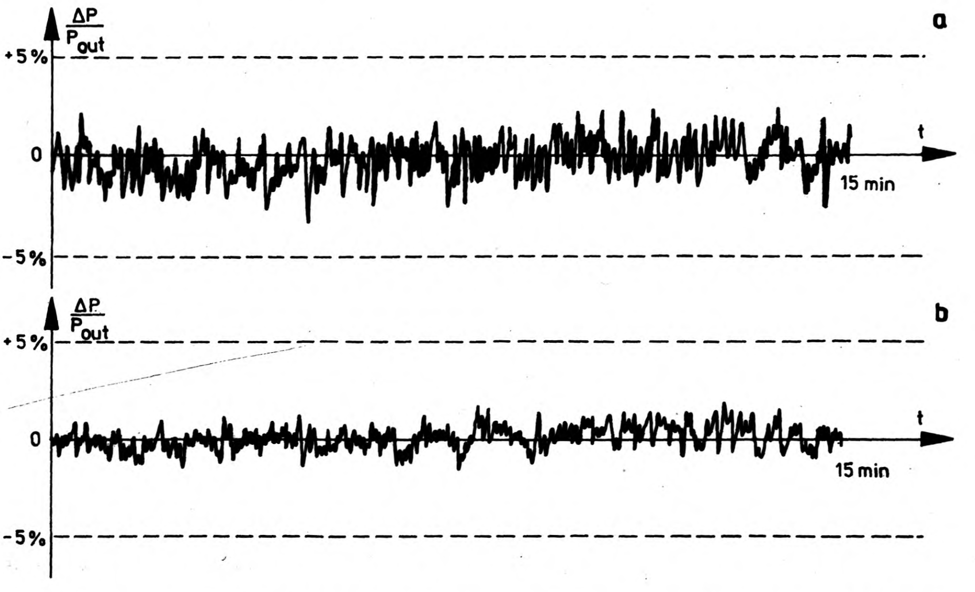


Fig. 2. Strip chart recorder plots of the $CO_2$ gas laser power fluctuations: (**a**) unstable laser output, (**b**) laser output when the frequency loop is closed

The power stabilization loop operates independently of the frequency stabilization loop. This statement has been confirmed experimentally by measuring the output power fluctuations at closed power stabilization loop, the frequency stabilization loop being switched-on or -off. Typical strip chart recorder plots are presented in Fig. 3. Reduction of the output power fluctuations was identical with the closed or open frequency stabilization loop.

The influence of the power stabilization loop on the frequency stability has been estimated implicitely. This influence was studied by measuring the maximal slope $\Delta P/P \Delta I$ of the output power $P$ versus DC discharge current intensity $I$ curves $P = f(I)$, and next by using Mocker's experimental data. The maximal slope has been calculated from $P = f(I)$ curves measured at different total gas pressures. This measurement and calculations have confirmed that the maximal slope is equal to $\Delta P/P \Delta I = 16\%/1$ mA. Taking into account both the optimal slope and the extent of the output power instabilities at closed frequency stabilization loop, $\pm 1.8\%/15$ min., the range of discharge current changes after closing the power stabilization loop can be estimated. During a 15 minute period the DC discharge current intensity will change within $\pm 0.11$ mA. Relative frequency changes connected with these current changes are within $\pm 10^{-9}$ according to both Mocker's and Kolosovskii's

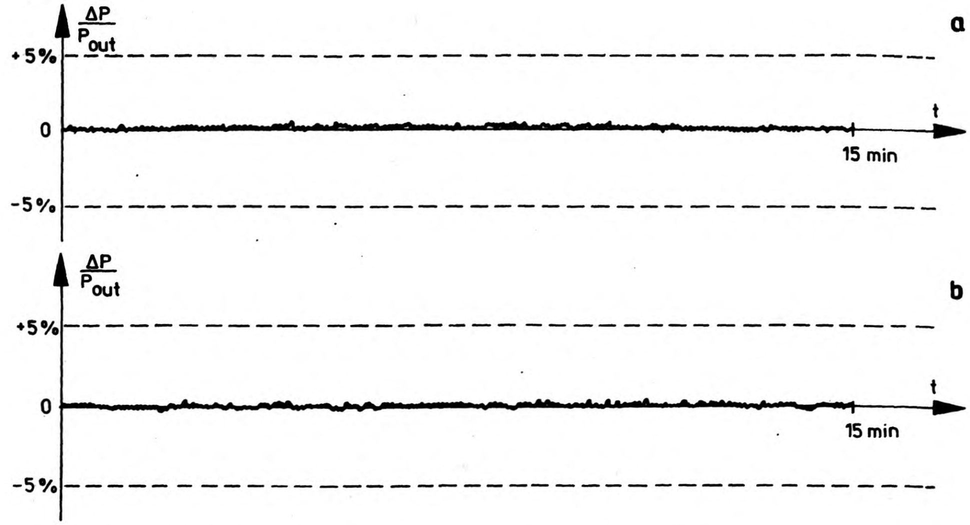


Fig. 3. Strip chart recorder plots of the $CO_2$ gas laser power fluctuations: (a) laser output when the power feedback loop is closed, (b) laser output when the frequency feedback loop is closed additionally

experimental data. The estimated frequency changes are one order below the value $10^{-8}$ which is typical of the chosen frequency stabilization method. Thus, in our experiment the frequency stability was the same, regardless of whether the power loop was closed or opened. In other words, the power loop did not influence the frequency stability.

## 5. Conclusions

Both the theoretical and experimental studies show that the double-stabilization system based on our conception ensures a simultaneous reduction of frequency and output power fluctuations. The interaction of both the stabilization feedback loops is neglected, since the stabilization factor of each of the systems does not depend on whether the second system is closed or opened. Thus, the double-stabilization system ensures the relative frequency stability of $10^{-8}$, thus value being typical of the chosen frequency stabilization system. At the same time, the double-stabilization system reduces the output power fluctuations to about $\pm 0.2\%/15$ min. making no worse the frequency stability.

It seems that the above statements will be valid when our conception of the double-stabilization system is used in other conventional $CO_2$ gas lasers provided that the work conditions of the $CO_2$ gas laser will be optimized.

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## Концепция конвенционального лазера $CO_2$ с двойной системой стабилизации

В работе представлено концепцию системы одновременной стабилизации частоты и выходной мощности лазера $CO_2$. Охарактеризовано проблемы связаны с собственным подбором системы стабилизации частоты и системы стабилизации мощности. Проанализовано вопросы взаимного воздействия контуров обратной связи избранных систем стабилизации. На основе качетвенного анализа и эксперимента констатировано, что предложена система гарантирует стабильность частоты выходного излучения выше чем $10^{-8}$ для времени усреднения одна секунда и одновременно стабильность выходной мощности $\pm 0,2\%$ в течение 15 минут.