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Tunable CO$_2$ laser emitting sequential and hot transitions

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Abstract. **The schematic model of a resonator with a reflection diffraction grating, providing a high frequency selectivivty, a wide spectral range, and a low loss level at a selected frequency, is studied theoretically and experimentally. The frequency-selective parameters of the resonator are calculated and analysed. It is shown that the dependence of the loss increment on the diaphragm diameter for a fixed frequency detuning $\Delta\nu$ is nonmonotonic. Lasing at 100 lines of conventional bands and 36 lines of sequential and hot transitions is obtained. The minimum separation $\Delta\nu_L$ between resolvable lines is found to be ~ 0.2 cm^{-1}.**

Keywords: *CO$_2$ laser, optical resonator, emission spectrum.*

1. Introduction

In recent years, considerable progress has been made in the field of ecological monitoring of the atmosphere by the optoacoustical spectroscopy using tunable CO$_2$ lasers [1, 2]. However, the potentialities of these lasers have not been exploited to the fullest extent since lasing in most of them has been realised only at conventional transitions.

At the same time, the presence of sequential and hot bands in emission spectra allows one to reduce the background signal level by two orders of magnitude, increase the sensitivity of measurements, and considerably extend the range of materials that can be detected by this method. Hence, the development of tunable CO$_2$ lasers emitting not only at the lines of traditional ($00^01 - [10^00, 02^00]$) bands, but also at the lines of sequential (00^0n – $[10^0(n-1), 02^0(n-1)]$) (for $n > 1$) and hot (01^11 – 11^10) bands is of considerable interest.

Note that the problem of selection of sequential and hot band lines is complicated in CO$_2$ lasers characterised by a wide range of emission spectra and a strong competition between laser transitions. This is due to a small separation between these lines and a large difference in the gain as compared to the corresponding values for the conventional transition lines.

There exists a selection method [3] that uses a heated intracavity cell filled with CO$_2$, which introduces selective losses at the main transitions. However, this method has a number of drawbacks: the destabilising effect of the heat source, additional nonselective losses, time lag in switching between transitions, and a larger size of the laser system.

Due to a small width of the spectral range, the selection problem cannot be solved by using resonators with interference elements having a high frequency selectivity. Combined resonators with two dispersion elements are complex and quite sensitive to misalignments.

In this paper, we consider the possibility of developing such a laser based on a standard commercial gas-discharge ILGN-501 tube with a diffraction grating as the dispersion element.

2. Choice of the resonator design

Attempts aimed at separating sequential transitions by using a resonator with a diffraction grating [4] led to the selection of the $P(27) - P(43)$ lines of the $00^02 - 10^01$ transition for which the minimum separation from the nearest main transition is 0.63 cm^{-1}.

Optimisation of the confocal parameter g and the Fresnel number N_F performed in Ref. [5] for a laser with a diffraction grating in an autocollimation setup with analogous [4] resonator length ($L_r \sim$ 137 cm) and active medium length ($L_a \sim 100$ cm) improved the situation only slightly: an additional line with $J = 25$, separated from the nearest main transition line by a distance 0.57 cm^{-1}, was selected in the P-branch of the $00^02 - 10^01$ transition. A further and significant improvement in the selectivity of this setup is possible only for much larger dimensions. Because the rate of increase in the losses due to detuning from the selected line is proportional to $\sqrt{L_r}$ (for fixed values of g and N_F) [6], a laser system of length no smaller than 5.5 m is required to double the selectivity.

This prompted us to use a design in which radiation is reflected twice from the diffraction grating during the round trip in the resonator. Figure 1a shows the configuration proposed by us. Unlike the setup described in [4] (see Fig. 1b), the diffraction grating in our setup is located between the mirrors and there is no second dispersion element – reflection interferometer (*5*) formed by highly reflecting mirror (*1*) and diffraction selector (*6*) [7].

A similar configuration was used in [8] for selecting sequential transitions. Our scheme differs from this confi-

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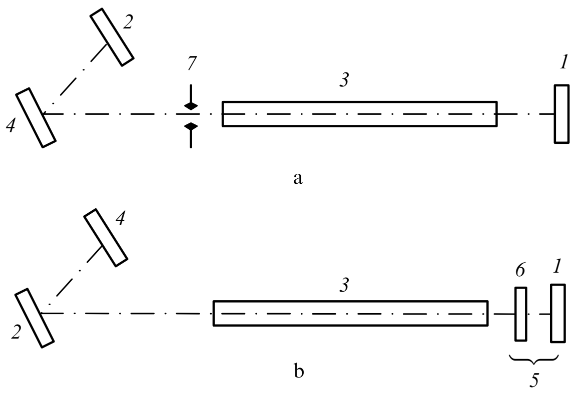

Figure 1. Scheme of (a) the investigated and (b) combined resonators: (*1*, *2*) spherical mirrors; (*3*) active medium; (*4*) diffraction grating; (*5*) reflection interferometer; (*6*) diffraction selector; (*7*) diaphragm.

guration in that it contains an aperture diaphragm (*7*) with a variable diameter d, which considerably affects the selectivity.

3. Calculation method and results

The loss level of the highest-Q transverse mode of the resonator is determined from the equation imposing the condition of self-reproduction (to within a constant factor) of the spatial field configuration after the round trip in the resonator,

$$\gamma u = \hat{K}u, \tag{1}$$

where u is the field distribution in a plane chosen as the reference plane, the operator $\hat{K}$ denotes field transformation after the round trip in the resonator, and the complex constant γ determines the mode attenuation and phase shift after the round trip.

Equation (1) was solved numerically by the iteration method [9, 10]. The field transformation during propagation between the optical elements of the resonator was calculated using the known expression

$$u(x_2,y_2)=\iint_{S_n}\frac{\exp(\mathrm{i}kL_m)}{\mathrm{i}\lambda L_m}\exp\left\{\frac{\mathrm{i}k}{2L_m}\left[(x_2-x_1)^2+(y_2-y_1)^2\right]\right\}u(x_1,y_1)\mathrm{d}x_1\mathrm{d}y_1, \tag{2}$$

where $u(x_1,y_1)$ is the initial field distribution in the plane of one of the elements; $u(x_2,y_2)$ is the field distribution after passing through a segment of length L_m $(m=1,2,3)$; and $k=2\pi/\lambda$. Integration was performed within the limits of circular aperture diaphragms S_n: $\{x\in[-A_n,A_n],\ y\in[-(A_n^2-x^2)^{1/2},(A_n^2-x^2)^{1/2}]\}$ $(n=1,2)$, where $2A_1$ is the aperture of the mirrors and the diffraction grating, and $2A_2=d$ is the diameter of diaphragm (*7*). Spherical mirrors (*1*) and (*2*) were treated as a quadratic phase corrector and their effect was taken into account by adding the phase factor $\exp[-(\mathrm{i}k/R_j)(x^2+y^2)]$ $(j=1,2)$. The diffraction grating was simulated by an equivalent plane mirror with a variable misalignment angle α related to the detuning $\Delta\nu=\nu-\nu_0$ relative to the selected frequency ν_0 by the expression $\alpha=(\Delta\nu/\nu_0)\tan\varphi_0$, where φ_0 is the autocollimation angle for the frequency ν_0. The field transformation after reflection from a plane mirror tilted at an angle α was taken into account by multiplying by the factor $\exp(-\mathrm{i}k2x\alpha)$. The lens effect during the propagation of radiation through the active medium was neglected.

The method described above was used to calculate the frequency-selectivity dependences and the level of nonselective losses in the wavelength range 9.2–11.2 μm for a resonator with the following parameters: separation between mirror (*1*) and the diaphragm was $L_1=125$ cm, separation between the diaphragm and the grating was $L_2\sim 13$ cm; and mirror (*2*) was at a distance $L_3=22$ cm from the grating. The radii of curvature of mirrors (*1*) and (*2*) were $R_1=3$ m and $R_2=7$ m, and the 150-lines mm^{-1} diffraction grating was used (the blaze angle was 54°). The diameters of the mirror and grating apertures were 14 mm and the diameter of the aperture diaphragm was varied between 5 and 8 mm.

The resonator properties were studied for different values of the diaphragm aperture. It was found that the level of nonselective losses a_0 decreases monotonically with increasing the diaphragm diameter from 5.0 to 8.0 mm. In particular, it varies from 40 % to 0.8 % in the region of 10.6 μm, covering virtually the entire range of losses acceptable for a laser with the active medium length ~100 cm (see Fig. 2). However, the dependence of the loss increment $\Delta a=a-a_0$ on the diaphragm diameter for a fixed fre-

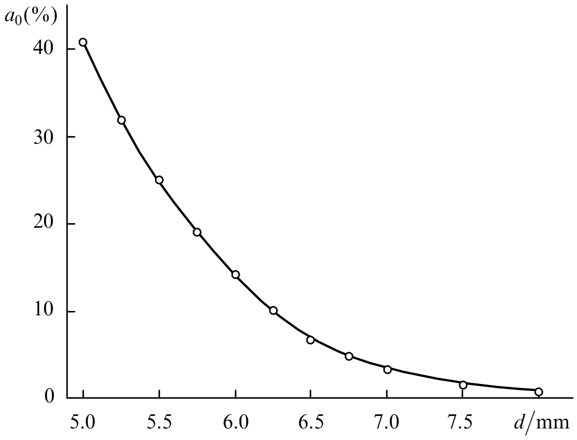

Figure 2. Dependence of the nonselective loss level a_0 on the diaphragm diameter d.

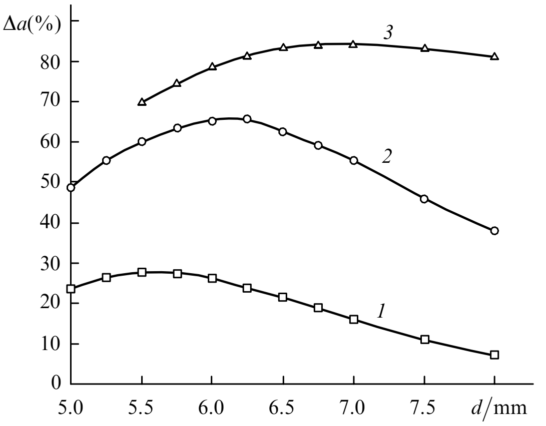

Figure 3. Dependence of the loss increment Δa on the diaphragm diameter d for a fixed value of the frequency detuning $\Delta\nu=10$ (*1*), 20 (*2*) and 35 GHz (*3*).

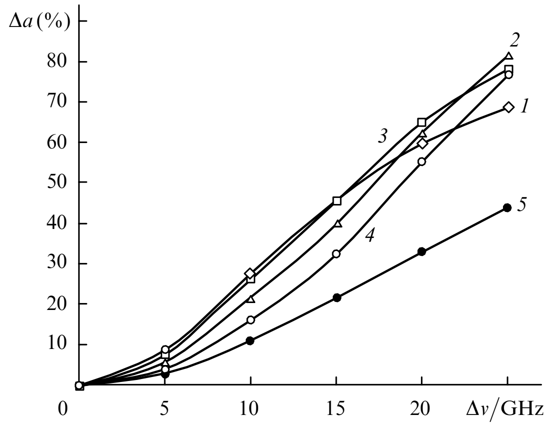

Figure 4. Dependence of the loss increment on frequency detuning for various values of the diaphragm diameter $d = 5.5$ (*1*), 6 (*2*), 6.5 (*3*) and 7 mm (*4*). Curve (*5*) is the dependence for the autocollimation scheme.

quency detuning $\Delta\nu$ is nonmonotonic. The diameter for which the maximum of selective losses is observed increases with $\Delta\nu$. Figure 3 shows the corresponding plots. For example, the highest loss increment $\Delta a = 28\,\%$ for a frequency detuning $\Delta\nu = 10$ GHz [curve (*1*)] is achieved for a diameter 5.5 mm. For detunings $\Delta\nu = 20$ and 35 GHz [curves (*2*) and (*3*), respectively], the corresponding values of d were 6.25 ($\Delta a = 66\,\%$) and 7 mm ($\Delta a = 84\%$).

Additional information on the resonator selectivity can be obtained from Fig. 4 showing the frequency dependences of losses for various diaphragm diameters. For comparison, the same figure also shows the steepest of such dependences for a resonator with a diffraction grating in an autocollimation setup (the resonator length and the dispersion of the grating are identical in both cases).

One can see from Fig. 4 that the selectivity of the configuration proposed by us is much better than that of the traditional autocollimation configuration. Moreover, the data given here can be used to select the size of the aperture diaphragm depending on the problem to be solved. In particular, the diaphragm diameter must be equal to 5.5 – 6 mm for selecting the closely spaced non-traditional lines ($\Delta\nu \leqslant 10$ GHz). At the same time, to suppress lines separated from the selected one by larger distances ($\Delta\nu \geqslant 25$ GHz), for example, for selecting the main transitions, the diameter d should be increased.

4. Experimental setup and results

The experimental setup shown in Fig. 5 is similar to the one described in [5]. A discretely tunable CO_2 laser consisted of active element (*2*) (a standard commercial gas-discharge ILGN-501 tube) with one spherical mirror (*4*) having a radius of curvature $R_1 = 3$ m. The length of the active medium was 100 cm. The spectral characteristics of laser radiation were measured with a panoramic spectrograph. The output power was measured with an IMO-4 power meter.

The CO_2 laser developed by us allows the selection of 100 lines of traditional bands, including 52 lines corresponding to the 00^01-10^00 [$P(4)-P(56)$ and $R(2)-R(50)$] transition and 48 lines corresponding to the 00^01-02^00 [$P(4)-P(52)$ and $R(4)-R(48)$] transition. Apart from this, lasing at 36 lines of sequential and hot bands was also observed. Of these, 17 lines correspond to the 00^02-10^01

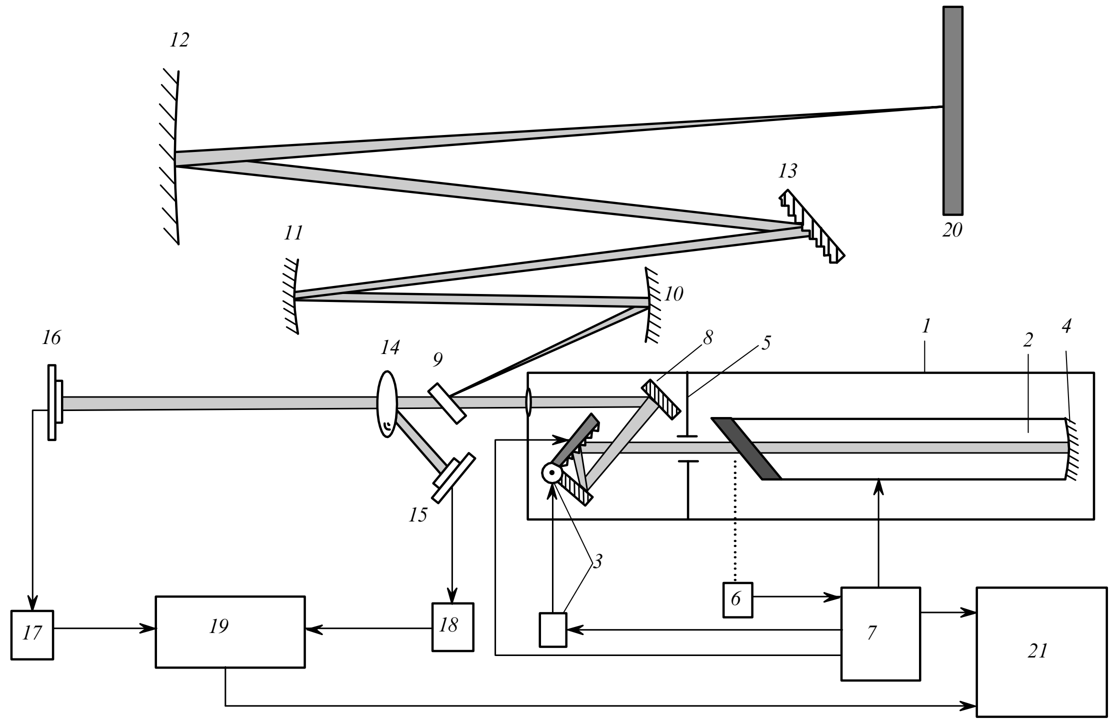

Figure 5. Scheme of the experimental setup: (*1*) housing; (*2*) active element; (*3*) diffraction grating with a corner reflector and a piezoelectric corrector; (*4*) highly reflecting mirror; (*5*) diaphragm; (*6*) sensor (MG-30); (*7*) power supply; (*8*) deflecting mirror; (*9*) semitransparent NaCl plate; (*10–12*) spherical mirrors; (*13*) diffraction grating; (*14*) chopper; (*15, 16*) sensors; (*17, 18*) amplifiers; (*19*) analogue-to-digital converter; (*20*) thermal screen; (*21*) PC.

Table 1.

The transition line number 00^02-10^01	Distance from the nearest main transition/cm^{-1}	Experimental conditions				
		[4]*	[5]*	[8]**	[4]***	Our results
$P(11)$	0.22	–	–	–	–	+
$P(13)$	0.27	–	–	–	+	+
$P(15)$	0.32	–	–	+	+	+
$P(17)$	0.37	–	–	+	+	+
$P(19)$	0.42	–	–	+	+	+
$P(21)$	0.48	–	–	+	+	+
$P(23)$	0.52	–	–	+	+	+
$P(25)$	0.57	–	+	+	+	+
$P(27)$	0.63	+	+	+	+	+
$P(29)$	0.66	+	+	+	+	+
$P(31)$	0.75	+	+	+	+	+
$P(33)$	0.81	+	+	+	+	+
$P(35)$	0.87	+	+	+	+	+
$P(37)$	0.92	+	+	+	+	+
$P(39)$	1.08	+	+	+	+	+
$P(41)$	1.04	+	+	–	+	+
$P(43)$	1.01	+	+	–	+	+

Note: * – Resonator with a diffraction grating in the autocollimation mode; **– Resonator with double reflection from the diffraction grating; ***– Resonator with a diffraction grating and a reflection interferometer.

$[P(11)-P(43)]$ transition and 19 lines to the 01^11-11^10 $[P(14)-P(32)]$ transition.

The minimum separation between the resolvable lines [sequential $P(11)$ line and the main $P(14)$ line in our case] is $\Delta\nu_L = 0.22\ \mathrm{cm}^{-1}$. The output power varied from 0.05–0.2 W at sequential and hot band lines to 1–3 W at the lines of main bands of the CO_2 molecule.

For comparison of the selective properties of various types of resonators, Table 1 shows the P-branch lines of the 00^02-10^01 transition and the frequency detunings to the corresponding nearest lines of the main 00^01-10^00 transition. The plus sign indicates lines selected earlier and in the present work using the following resonator schemes: with a diffraction grating in the autocollimation mode, with two reflections from the diffraction grating during the round trip, and with two dispersion elements (interferometer and diffraction grating).

One can see from Table 1 that the results obtained by us are superior to those obtained in earlier works even with more complicated combined resonators for which $\Delta\nu_L = 0.27\ \mathrm{cm}^{-1}$ for the same length of the active medium (1 m). A more noticeable improvement is observed compared to the results obtained in [8] using a similar resonator scheme. For a longer (1.5 m) active medium in [8], a resolution $\Delta\nu_L = 0.32\ \mathrm{cm}^{-1}$ was obtained and the number of lines selected in the P-branch of the 00^02-10^01 transition was smaller by four.

5. Conclusions

We have investigated theoretically and experimentally a resonator scheme with a reflection diffraction grating providing a high frequency selectivity, a broad spectral range, and a low loss level at a selected frequency.

The frequency-selective properties of the resonator have been calculated and analysed. It has been shown that the dependence of the loss increment on the diaphragm diameter for a fixed frequency detuning $\Delta\nu$ is nonmonotonic. The diameter at which the maximum of selective losses is observed increases with $\Delta\nu$, which makes it possible to choose the optimal size of the diaphragm aperture for each of the problems being solved.

For an active medium length of ~100 cm, the tunable CO_2 laser developed by using the scheme described here makes it possible to select 100 traditional band lines as well as 36 sequential and hot transition lines.The minimum separation $\Delta\nu_L$ between the resolved lines is $\sim 0.2\ \mathrm{cm}^{-1}$.

These results are better than the results obtained earlier using a similar scheme with a longer active medium (150 cm), which provides the resolution $\Delta\nu_L \sim 0.3\ \mathrm{cm}^{-1}$, as well as combined resonators with two dispersion elements for the same length of the active medium.

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