

SPECTROSCOPY OF AMBIENT MEDIUM

Multifrequency Laser Diagnostics of Vibrational Nonequilibrium Gas Media Containing CO₂ Molecules

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Abstract—The technique for multifrequency diagnostics of a vibrational nonequilibrium gas mixture that contains CO₂ molecules is proposed. The technique uses data on unsaturated gains at lines of the 00⁰1–[10⁰0, 02⁰0]_{I,II} and 00²–[10⁰1, 02⁰1]_{I,II} transitions obtained with the help of a tunable CO₂ laser. Results of the study of the influence of accuracy of gain measurements and the number of sensing lines on errors in determining populations of vibrational levels and gas mixture translational temperatures are presented.

Keywords: vibrational nonequilibrium gas media, CO₂ molecules, multifrequency sensing, level population, translational gas temperature

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INTRODUCTION

Vibrational nonequilibrium gas mixtures as monomolecular gases or their mixtures refer to substances being under conditions of failure of the law of homogeneous energy distribution over translational or inner vibrational and rotational degrees of freedom. Under such conditions in nonequilibrium media, the energy exchange between different degrees of freedom proceeds, which influences physical processes in them, in particular, parameters of generation of nonequilibrium structures. As a consequence, corresponding properties of nonequilibrium and equilibrium gas media differ; therefore, these media are objects of various studies (see, for example, [1, 2]). Active media of gas-discharge and gas-dynamic CO₂ lasers [3–6] include such media, as well as media generated in the upper atmospheric layers of the Earth and other planets, during shock wave propagation in the atmosphere, or during intensive burning of hydrocarbon fuels [7, 8].

The diagnostics of vibrational nonequilibrium gas media is performed by different methods, having different capabilities and application conditions (see, e.g., [9, 10]). The method of laser spectrograph with the use of a frequency-stabilized tunable CO₂ laser as a source of sensing radiation is the most adequate and convenient for diagnostics of both equilibrium and nonequilibrium gas media containing CO₂ molecules [11–14].

The technique for multifrequency sensing of vibrational nonequilibrium mixture containing CO₂ molecules is described in this paper. It is based on the use of tunable CO₂ laser measurements of unsaturated gains

at lines of the 00⁰1–[10⁰0, 02⁰0]_{I,II} and 00²–[10⁰1, 02⁰1]_{I,II} transitions of CO₂ molecules. Results of the study of the influence of measurement accuracy of gains and the number of sensing lines on errors in determination of populations of the used vibrational levels and translational temperature of the gas mixture are also presented.

DIAGNOSTICS TECHNIQUE

An expression for the unsaturated gain at the line center of 00⁰1–[10⁰0, 02⁰0]_{I,II} or 00²–[10⁰1, 02⁰1]_{I,II} transitions of CO₂ molecules in a vibrational nonequilibrium gas mixture containing CO₂ molecules can be written as [11]:

$$K_{li,2i} = \frac{\lambda_{0li,2i}^2}{8\pi} A_{li,2i} C'_{li,2i} \frac{2hcB_m}{kT} \times \left\{ N_m \exp \left[-C''_{li,2i} \frac{hcB_m}{kT} \right] - N_{n1,n2} \frac{B_{n1,n2}}{B_m} \right. \quad (1)$$

$$\left. \times \exp \left[-J_{li,2i} (J_{li,2i} + 1) \frac{hcB_{n1,n2}}{kT} \right] \right\} F_{li,2i},$$

where index 1 relates to the 00⁰1–10⁰0 or 00²–10⁰1 transition, index 2, to 00⁰1–02⁰0 or 00²–02⁰1 transition, m , to the upper laser level, and n , to the lower one; $\lambda_{0li,2i}$ is the wavelength at the line center [15]; $A_{li,2i}$ is the Einstein coefficient [15]; $F_{li,2i}$ is the form factor at the center of the i th line; $J_{li,2i}$ is the rotational quan-

tum number; $C'_{li,2i} = 2J_{li,2i} - 1$, $C''_{li,2i} = J_{li,2i}(J_{li,2i} - 1)$ for lines of P -branches; $C'_{li,2i} = 2J_{li,2i} + 3$, $C''_{li,2i} = (J_{li,2i} + 1)(J_{li,2i} + 2)$ for lines of R -branches; $B_{001} = 0.3871 \text{ cm}^{-1}$, $B_{100} = 0.3902 \text{ cm}^{-1}$, $B_{020} = 0.3905 \text{ cm}^{-1}$ are the rotational constants [16]; c is the speed of light; h is Planck's constant; and k is Boltzmann's constant.

The pressure of nonequilibrium gas media can lie in a range from units of Torr to atmospheric pressure, and the contributions of the Doppler effect and collision processes into the spectral line broadening can differ for different pressures in this range. The use of the expression for the form factor at the center of line of a mixed or Voigt profile, taking into account contributions from both effects, seems to be the most optimal. The expression for the form factor at the center of Voigt profile $F_{li,2i}$ has the form [17]:

$$F_{li,2i} = \frac{2\sqrt{\ln 2}}{\sqrt{\pi}\Delta v_{Dli,2i}} \left\{ \frac{a}{x_{li,2i} + [(bx_{li,2i})^q + \pi]^{1/2}} \right\}, \quad (2)$$

where $x_{li,2i} = (\Delta v_{Lli,2i}/\Delta v_{Dli,2i})(\ln 2)^{1/2}$, $\Delta v_{Lli,2i} = \gamma_{li,2i}(\xi_{\text{CO}_2} + C_{N_2} \xi_{N_2} + C_{\text{He}} \xi_{\text{He}}) p_{\Sigma} (300/T)^{1/2}$ is the collisional (Lorentz) line width [18], C_{N_2} and C_{He} are the relative coefficients of collisional broadening of the i th line by N_2 molecules and He atoms [19], $\gamma_{li,2i}$ is the coefficient of collisional broadening of the i th line [15], p_{Σ} is the total gas pressure, ξ_{CO_2} , ξ_{N_2} , and ξ_{He} are the fractions of CO_2 , N_2 , and He in the gas mixture, T is the translational gas temperature; $\Delta v_{Dli,2i} = (v_{0li,2i}/c)(kT \ln 4/M_{\text{CO}_2})^{1/2}$ is the Doppler line width, $v_{0li,2i}$ is the central frequency of the i th line [15], M_{CO_2} is the mass of CO_2 molecule; $a = \pi^{1/2}/2$; $b = (\pi - 2)/2$; $q = 2$.

If the gains for a vibrational nonequilibrium medium are measured, then the gas temperature T and populations of vibrational levels N_m and N_{n1} , N_{n2} remain unknown in Eq. (1). The connection between the sought parameters $\{N_{n1}, N_{n2}, N_m, T\}$ and gain $\{k_{1i}, k_{2i}\}$ measurements at lines of both transitions is defined by the redundant system of equations

$$\begin{cases} k_{1i} = K_{1i}(N_{n1}, N_m, T), \\ k_{2i} = K_{2i}(N_{n2}, N_m, T), \end{cases} \quad (3)$$

where k_{1i} and k_{2i} are the results of the i th gain measurement at lines of both transitions. Let us note the difference between diagnostics of vibrational equilibrium and vibrational nonequilibrium gas mixtures containing CO_2 molecules. In the first case, the inverse problem is solved, when based on the measured spectral distribution of laser radiation absorption coefficients, two sought parameters are determined simultaneously: the gas mixture temperature T and partial

pressure CO_2 p_{CO_2} . In the second case, based on the measured spectral distributions of the laser radiation gains, four parameters are determined simultaneously: gas mixture temperature T , populations of the upper N_m and two lower vibrational levels N_{n1} and N_{n2} of the considered transitions. System of equations (3) can be solved by the least squares method, through minimization of the functional

$$Z = \sum_{i=1}^S w_{1i}(k_{1i} - K_{1i})^2 + \sum_{i=1}^S w_{2i}(k_{2i} - K_{2i})^2, \quad (4)$$

where w_{1i} and w_{2i} are the weight coefficients.

At any set temperature T , system of linear equations

$$\begin{cases} -N_{n1}H_1 + N_mH_2 = H_3, \\ -N_{n2}H_4 + N_mH_5 = H_6, \\ -N_{n1}H_7 - N_{n2}H_8 + N_mH_9 = H_{10} \end{cases} \quad (5)$$

(where coefficients H_1 – H_{10} are represented through parameters entering in Eqs. (1) and (2), and are omitted here because of their awkwardness) corresponds to

$$\text{conditions } \frac{\partial Z}{\partial N_{n1}} = 0, \frac{\partial Z}{\partial N_{n2}} = 0, \frac{\partial Z}{\partial N_m} = 0.$$

The calculation algorithm is the following: system of equations (5) is solved at certain minimal temperature T_{\min} and functional Z (4) minimal for the given temperature is calculated on the basis of the found values of level populations (N_{n1} , N_{n2} , N_m); then the temperature T is varied in the set temperature range T_{\min} – T_{\max} , and the minimal functional Z is found for this range. For the first iteration, the weight coefficients are taken equal to unity, i.e., $w_{1i}^1 = 1$ and $w_{2i}^1 = 1$, and for the $(j + 1)$ th step [20],

$$\begin{aligned} w_{1i}^{j+1} &= \frac{1}{[k_{1i} - K_{1i}(N_{n1}^j, N_m^j, T^j)]^2}, \\ w_{2i}^{j+1} &= \frac{1}{[k_{2i} - K_{2i}(N_{n2}^j, N_m^j, T^j)]^2}. \end{aligned} \quad (6)$$

The use of the weight coefficients allows us to decrease the influence of gains measured with a high error on the accuracy of the final result.

CALCULATION RESULTS

In order to analyze capabilities of the suggested technique for multifrequency sensing, the model of vibrational nonequilibrium gas mixture $\text{CO}_2 : N_2 : \text{He} = 5 : 10 : 85$ at a total pressure of 80 Torr was used. For that mixture, an arbitrary value of the translational temperature $T = 360 \text{ K}$ and three sets of populations of the vibrational levels 00^01 $N_m = (7.82 \times 10^{21} \text{ m}^{-3}, 1.6 \times 10^{22} \text{ m}^{-3}, \text{ and } 2.04 \times 10^{22} \text{ m}^{-3})$, 10^00 $N_{n1} = 1.7 \times 10^{21} \text{ m}^{-3}$, and 02^00 $N_{n2} = 2.11 \times 10^{21} \text{ m}^{-3}$

Relative errors of populations of vibrational levels δN_{n1} , δN_{n2} , and δN_m and of gas mixture temperature δT for different degrees of vibrational nonequilibrium and the standard deviation of gain $\sigma_k = 0.02 \text{ m}^{-1}$

Parameter	$N_m = 7.82 \times 10^{21}$, $N_{n1} = 1.7 \times 10^{21}$, $N_{n2} = 2.11 \times 10^{21}, \text{ m}^{-3}$	$N_m = 1.6 \times 10^{22}$, $N_{n1} = 1.7 \times 10^{21}$, $N_{n2} = 2.11 \times 10^{21}, \text{ m}^{-3}$	$N_m = 2.04 \times 10^{22}$, $N_{n1} = 1.7 \times 10^{21}$, $N_{n2} = 2.11 \times 10^{21}, \text{ m}^{-3}$
$\delta N_{n1}, \%$	3.50	7.5	3.3
$\delta N_{n2}, \%$	3.30	5.1	1.0
$\delta N_m, \%$	3.30	3.5	2.7
$\delta T, \%$	0.01	0.1	0.1

were determined, corresponding to different degrees of the vibrational nonequilibrium in the mixture (Table). The gains were calculated by Eqs. (1) and (2). Due to superimposition of Gaussian noise on the calculated gains with the help of the normrnd function (from MatlabR12 software), experimental gains $\{k_{1i}, k_{2i}\}$ have been formed. The noise level was calculated in percentages of a minimal gain in the considered spectral region ($J = 6-34$) and was taken to be equal to 3%, which approximately corresponded to the standard deviation $\sigma_k = 0.02 \text{ m}^{-1}$.

The standard deviations of the sought parameters $\sigma_{N_{n1}}, \sigma_{N_{n2}}, \sigma_{N_m}, \sigma_T$ were calculated through calculations of covariance matrices [20, 21]. In our case, it was a 4×4 matrix with diagonal elements $\sigma_{N_{n1}}^2, \sigma_{N_{n2}}^2, \sigma_{N_m}^2, \sigma_T^2$. In the general case, the connection between covariance matrices of directly $\{k_{1i}, k_{2i}\}$ and indirectly

$\{N_{n1}, N_{n2}, N_m, T\}$ measured parameters can be written in the form

$$COV = (b^T COV_k^{-1} b)^{-1}, \quad (7)$$

where b is the matrix with elements $b_{ij} = \frac{\partial K_{1i, 2i}}{\partial y_j}$ ($j = 1-4$; $y_1 = N_{n1}, y_2 = N_{n2}, y_3 = N_m, y_4 = T$) at the point of quasi-solution; b^T is the transposed matrix b . With direct noncorrelated measurements of gains $\{k_{1i}, k_{2i}\}$ with the standard deviation σ_k , expression (7) takes the form

$$COV = \sigma_k^2 (b^T b)^{-1}. \quad (8)$$

Expression (8) connects the standard deviations of the required parameters $\sigma_{N_{n1}}, \sigma_{N_{n2}}, \sigma_{N_m}, \sigma_T$ with those of input data, i.e., measured gains, σ_k . Figure 1 shows dependencies of the standard deviations σ_{N_m} of population of the upper level 00^01 on the number of sensing lines n for $\sigma_k = 0.02 \text{ m}^{-1}$. Similar dependencies are determined for the standard deviations $\sigma_{N_{n2}}$ and $\sigma_{N_{n1}}$ of populations of the lower levels 02^00 and 10^00 , respectively, and standard deviation for the temperature σ_T . It is seen that the method accuracy grows as the number of sensing lines increases and in the case of simultaneous use of sensing lines of both vibrational transitions $00^01-[10^00, 02^00]_{I, II}$. The number of lines no less than 30 is optimal.

The table shows relative errors of the desired parameters $\delta N_{n1}, \delta N_{n2}, \delta N_m$, and δT , found immediately from solution of the inverse problem when the level populations and temperature have been found by the above-described technique. In calculations, gains of 60 lines of the $00^01-[10^00, 02^00]_{I, II}$ transitions were used. The calculation results presented in the Table show that the accuracy is almost unchangeable within the considered region of nonequilibrium populations of the vibrational levels $00^01, 10^00$, and 02^00 .

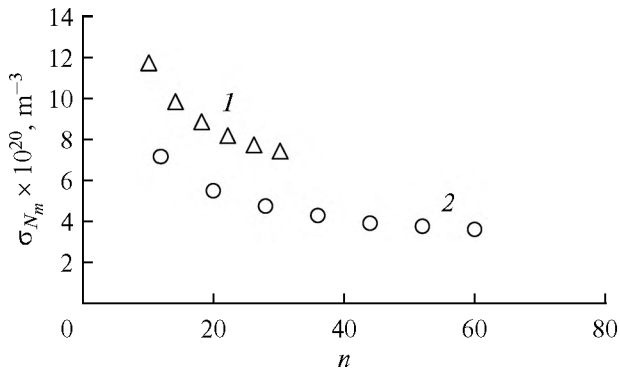


Fig. 1. Standard deviation σ_{N_m} of the population of 00^01 level as a function of the number of sensing lines n for $\sigma_k = 0.02 \text{ m}^{-1}$ at the use of gains at lines of P - and R -branches of one transition 00^01-10^00 (1) and both transitions 00^01-10^00 and 00^01-02^00 (2).

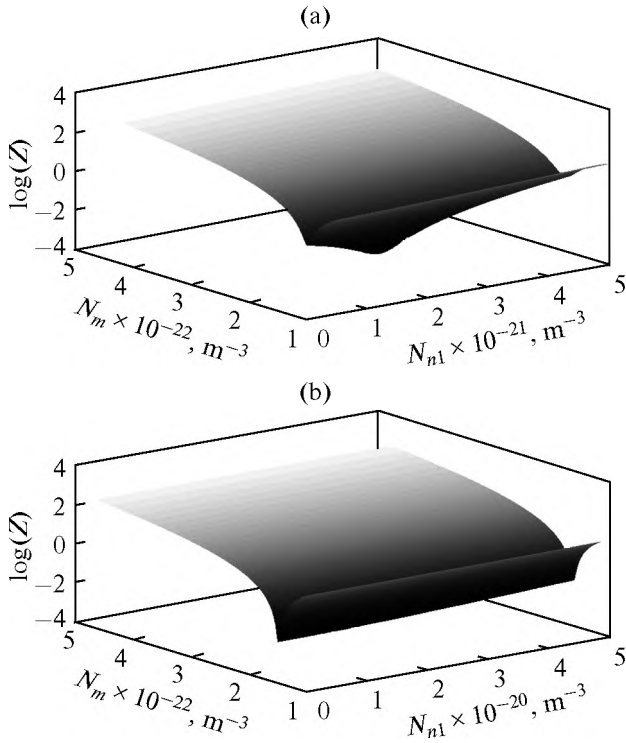


Fig. 2. Dependencies of $\log(Z)$ on the populations of vibrational levels $00^01 N_m$ and $10^00 N_{n1}$ at the standard deviation of gain measurements $\sigma_k = 0.02 \text{ m}^{-1}$: (a) $N_m/N_{n1} = 10$ and (b) $N_m/N_{n1} = 200$.

Evidently, system of equations (5), provided it has a solution, corresponds to the presence of a global minimum of functional Z (4). The graphical plotting of Z is a simple and informative way of finding the global minimum when analyzing the influence of different experimental conditions, for example, gain measurement errors. To visualize Z , we used a set of 60 gains for lines of primary vibrational transitions $00^01-[10^00, 02^00]_{I,II}$ of CO_2 . Figure 2 shows dependencies of the functional $\log(Z)$ on populations of the vibrational levels $00^01 N_m$ and $10^00 N_{n1}$ at the standard deviation of gain measurement $\sigma_k = 0.02 \text{ m}^{-1}$ for $N_m/N_{n1} = 10$ and $N_m/N_{n1} = 200$. It is seen that at the inversion, exceeding a certain value, the global minimum of Z is transformed into the cavity (Fig. 2b), and the population of the lower vibrational level 10^00 of CO_2 cannot be found correctly. When considering the dependence of the functional $\log(Z)$ on the population of vibrational levels $00^01 N_m$ and $02^00 N_{n2}$, a similar result is obtained.

Smearing of the global minimum of the functional Z also takes place at an increase in the standard deviation of gain measurements (Fig. 3).

Based on data of Fig. 1, the conclusion can be drawn that calculation results are the most accurate in the case where the gain of P - and R -branches of both

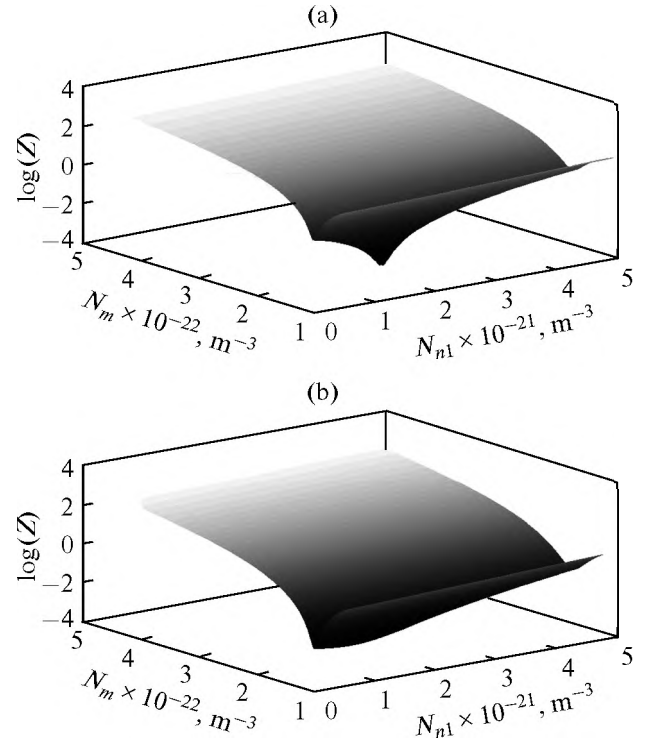


Fig. 3. Dependencies of $\log(Z)$ on the populations of vibrational levels $00^01 N_m$ and $10^00 N_{n1}$ at 60 sensing lines and the standard deviations of gain measurement (a) $\sigma_k = 0.007 \text{ m}^{-1}$ and (b) $\sigma_k = 0.07 \text{ m}^{-1}$.

vibrational transitions $00^01-[10^00, 02^00]_{I,II}$ or $00^02-[10^01, 02^01]_{I,II}$ are used.

Thus, the technique for multifrequency laser diagnostics of the vibrational nonequilibrium gas mixture containing CO_2 molecules allows us to determine with high accuracy not only the population of upper level N_m ($\delta N_m < 4\%$) and the temperature T ($\delta T < 1\%$), but also the population of the lower levels N_{n1} ($\delta N_{n1} < 8\%$), N_{n2} ($\delta N_{n2} < 6\%$) in the case of simultaneous use of gains of lines of the vibrational transition $00^01-[10^00, 02^00]_{I,II}$ or $00^02-[10^01, 02^01]_{I,II}$, when the input data (gain) accuracy meets the condition $\sigma_k = 0.03k_{\min}$, where k_{\min} is the minimally measured gain.

The developed technique for multifrequency diagnostics of vibrational nonequilibrium gas mixture containing CO_2 molecules was also applied to the analysis of actual experimental data, i.e., results of measurements of unsaturated gains in the active medium of a transversely excited CO_2 laser at a pressure of 80 Torr at lines of P - and R -branches of primary laser transitions $00^01-[10^00, 02^00]_{I,II}$ and transitions of the first sequential band $00^02-[10^01, 02^01]_{I,II}$ [22]. From the data presented in [22], the $10P(12)$, $10P(20)$, $9P(18)$, $9P(22)$, $9R(10)$, $9R(12)$, $9R(18)$, and $9R(24)$ lines of the $00^01-[10^00, 02^00]_{I,II}$ transitions and $10P(15)$,

$10P(25)$, $10R(31)$, and $9R(17)$ lines of the 00^0_2 – $[10^0_1, 02^0_1]_{I,II}$ transitions with measured abnormal gains were excluded, as well as $10P(14)$, $10P(18)$, $10P(28)$, $10P(34)$, $9P(10)$, $9R(14)$, $9R(30)$, and $9R(32)$ lines of the 00^0_1 – $[10^0_0, 02^0_0]_{I,II}$ transitions, which are overlapped with lines of hot 11^1_0 – 01^1_1 , 03^1_0 – 01^1_1 transitions (see, e.g., [13]). We have calculated the translational temperature of the active medium and populations of laser vibrational levels 00^0_1 , 10^0_0 , 02^0_0 , 00^0_2 , 10^0_1 , and 02^0_1 :

$$\begin{aligned} T &= (366.8 \pm 0.3) \text{ K}, \\ N_{001} &= (1.816 \pm 0.01) \times 10^{22} \text{ m}^{-3}, \\ N_{020} &= (2.087 \pm 0.07) \times 10^{21} \text{ m}^{-3}, \\ N_{100} &= (1.817 \pm 0.06) \times 10^{21} \text{ m}^{-3}; \\ T &= (364.6 \pm 1.1) \text{ K}, \\ N_{002} &= (4.529 \pm 0.03) \times 10^{21} \text{ m}^{-3}, \\ N_{021} &= (3.359 \pm 0.04) \times 10^{20} \text{ m}^{-3}, \\ N_{101} &= (2.348 \pm 0.03) \times 10^{20} \text{ m}^{-3}. \end{aligned}$$

These results show that the assumption used by the authors of [22] that the populations of lower vibrational levels are significantly less than the populations of upper vibrational levels of laser transitions in the active medium of a transversely excited CO_2 laser does not conform to reality.

CONCLUSIONS

The developed technique for multifrequency laser diagnostics of vibrational nonequilibrium gas medium containing CO_2 molecules is based on measurements of unsaturated gains at lines of the 00^0_1 – $[10^0_0, 02^0_0]_{I,II}$ and 00^0_2 – $[10^0_1, 02^0_1]_{I,II}$ transitions of CO_2 molecules and allows one to determine the medium translational temperature and populations of the corresponding levels. Capabilities of the technique proposed were analyzed with the help of the model of vibrational nonequilibrium gas mixture, and it was shown that the diagnostic results are the most accurate when the gains are measured at no less than 30 lines of P - and R -branches of both vibrational transitions 00^0_1 – $[10^0_0, 02^0_0]_{I,II}$ or 00^0_2 – $[10^0_1, 02^0_1]_{I,II}$. It is shown that if the standard deviations of the gains measured meet the condition $\sigma_k = 0.03k_{\min}$, then the technique allows one to find the population of upper vibrational level N_m with the relative error $\delta N_m < 4\%$, of the lower level N_{n1} with $\delta N_{n1} < 8\%$, of the lower level N_{n2} with $\delta N_{n2} < 6\%$, and the translation temperature T with $\delta T < 1\%$. The technique was tested by results of gain measurements in the active medium of an actual transversely excited CO_2 laser.

REFERENCES

1. A. I. Osipov and A. V. Uvarov, "Stability problems in a non-equilibrium gas," *Phys.-Uspekhi* **39** (6), 597–608 (1996).
2. A. I. Osipov and A. V. Uvarov, "Physics of a nonequilibrium gas," *Priroda* (Moscow, Russ. Fed.), No. 10, 61–68 (2001).
3. W. J. Witteman, *The CO_2 Laser* (Springer, 1987).
4. J. D. Anderson, *Gas-Dynamic Lasers: An Introduction* (Academic, New York, 1976).
5. *Handbook of Chemical Lasers*, Ed. by R. Grossa and J. Botr (John Wiley & Sons, New York, 1976).
6. A. S. Boreisho, "High-power mobile chemical lasers," *Quantum Electron.* **35** (5), 393–406 (2005).
7. V. S. Letokhov, "Lasing in space," *Phys.-Uspekhi* **45** (12), 1306–1310 (2002).
8. V. D. Rusanov and A. A. Fridman, *Physics of Chemically Active Plasma* (Nauka, Moscow, 1981) [in Russian].
9. O. V. Achasov, N. N. Kudryavtsev, S. S. Novikov, R. I. Soloukhin, and N. A. Fomin, *Diagnostics of Nonequilibrium States in Molecular Lasers* (Nauka i tekhnika, Minsk, 1985) [in Russian].
10. V. K. Zhivotov, V. D. Rusanov, and A. A. Fridman, *Diagnostics of Nonequilibrium Reactive Plasma* (Energoatomizdat, Moscow, 1985) [in Russian].
11. K. I. Arshinov, N. S. Leshenyuk, and V. V. Nevdakh, "Calculation of the vibrational temperatures and populations of the laser-active levels of CO_2 from the spectral distribution of the gain," *Quantum Electron.* **28** (8), 659–662 (1998).
12. K. I. Arshinov, N. S. Leshenyuk, and V. V. Nevdakh, "Multifrequency diagnostics of a vibrationally equilibrium CO_2 -containing gas mixture," *J. Appl. Spectrosc.* **68** (6), 942–948 (2001).
13. K. I. Arshinov, M. K. Arshinov, V. V. Nevdakh, M. Y. Perin, A. Soufiani, and V. V. Yasnov, "Accuracy in determination of the temperature and partial pressure of CO_2 in $\text{CO}_2 : \text{N}_2 : \text{H}_2\text{O} : \text{NO}_2$ mixtures by multiple-frequency laser probing," *J. Appl. Spectrosc.* **74** (6), 903–909 (2007).
14. K. I. Arshinov, O. N. Krapivnaya, and V. V. Nevdakh, "Laser diagnostics of equilibrium a $\text{CO}_2 : \text{N}_2$ gas mixture," *Atmos. Ocean. Opt.* **27** (5), 381–385 (2014).
15. L. S. Rothman, I. E. Gordon, Y. Babikov, A. Barbe, C. D. Benner, P. F. Bernath, M. Birk, L. Bizzocchi, V. Boudon, L. R. Brown, A. Campargue, K. Chance, E. A. Cohen, L. H. Coudert, V. M. Devi, B. J. Drouin, A. Fayt, J.-M. Flaud, R. R. Gamache, J. J. Harrison, J.-M. Hartmann, C. Hill, J. T. Hodges, D. Jacquemart, A. Jolly, J. Lamouroux, R. J. Le Roy, G. Li, D. A. Long, O. M. Lyulin, C. J. Mackie, S. T. Massie, S. Mikhailenko, H. S. P. Muller, O. V. Naumenko, A. V. Nikitin, J. Orphal, V. Perevalov, A. Perrin, E. R. Polovtseva, C. Richard, M. A. H. Smith, E. Starikova, K. Sung, S. Tashkun, J. Tennyson, G. C. Toon, V. G. Tyuterev, and G. Wagner, "The

- HITRAN 2012 molecular spectroscopic database,” *J. Quant. Spectrosc. Radiat. Transfer* **130**, 4–50 (2013).
16. T. J. Bridges and T. Y. Chang, “Accurate rotational constants of CO₂ from measurements of cw beats in bulk GaAs between CO₂ vibrational-rotational laser lines,” *Phys. Rev. Lett.* **22**, 811–815 (1969).
 17. V. P. Kudrya, “Calculation of the Voigt function value at the line center,” *Opt. Spektrosk.* **55** (6), 113–114 (1983).
 18. R. L. Abrams, “Broadening coefficients for the *P*(20) CO₂ laser transition,” *Appl. Phys. Lett.* **25** (10), 609–611 (1974).
 19. M. O. Bulanin, V. P. Bulychev, and E. B. Khodos, “Calculation of parameters of rovibrational lines in 9.4 and 10.4 μm CO₂ bands at different temperatures,” *Opt. Spektrosk.* **48** (4), 732–737 (1980).
 20. V. I. Mudrov and V. L. Kushko, *Measurement Processing Techniques* (Radio i svyaz', Moscow, 1983) [in Russian].
 21. N. S. Leshenyuk and V. V. Pashkevich, “Accuracy characteristics in the diagnostics of active media of CO₂ lasers from gain coefficient measurements,” *J. Appl. Spectrosc.* **46** (4), 354–359 (1987).
 22. R. K. Brimacombe and J. Reid, “Measurements of anomalous gain coefficients in transversely excited CO₂ laser,” *IEEE J. Quantum Electron.* **19** (11), 1674–1679 (1983).

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