CHARACTERISTICS OF A GAS-DISCHARGE CO-LASER EMITTING AT A HARMONIC, PART 2: SIMULTANEOUS EMISSION AT FUNDAMENTAL AND SECOND-HARMONIC FREQUENCIES IN THE PULSE MODE

Yu. B. Konev, I. V. Kochetov,
A. K. Kurnosov, V. G. Pevgov,
and A. V. Dem'yanov

UDC 621.375.826

The characteristics of a gas-discharge CO-laser operating simultaneously at fundamental and second-harmonic frequencies in the pulse mode are theoretically analyzed.

In a gas-discharge CO-laser the gain at the second-harmonic frequency can differ by an order of magnitude or more from the gain at the fundamental frequency [1]. It is very difficult in practice to construct a resonator featuring high losses (below the emission threshold) at wavelengths of the fundamental transition and small losses at the second-harmonic wavelengths. This is particularly difficult to attain for a pulse mode of operation at a low gas temperature, at which the gain at the fundamental frequency can reach 5-10 m^{-1}. Consequently, in experimental studies [2, 3] emission occurred simultaneously at the fundamental frequency and at the second-harmonic frequency with the most intense emission lines at the fundamental frequency corresponding to the lower levels, levels with either a very weak or with no amplification at the second-harmonic frequency. Higher levels where transitions from one to another can stimulate emission at the second-harmonic frequency become populated during VV-exchange processes. During emission at the fundamental frequency the energy flux toward those levels becomes less intense, while the gain at the second-harmonic frequency decreases and begins to depend not only on the pumping as well as on the composition and the temperature of the gas but also on the conditions of emission at the fundamental frequency. There has been an interest in studying the effect of emission at the fundamental frequency on emission at the second-harmonic frequency. In an earlier study [4] a pulse-mode CO-laser operating at the second-harmonic frequency has been analyzed on the assumption that the emission threshold at the fundamental frequency is not reached. In this study the characteristics of a CO-laser (gain, efficiency, spectral content of emission) emitting pulses of up to 100 μsec duration and the dependence of these characteristics on the gas temperature, the energy density, and the resonator losses at the fundamental frequency will be theoretically analyzed.

The problem has already been formulated in terms of kinetic processes in the active medium [5, 6] and, therefore, we will here consider only modifications necessary for calculating the characteristics of simultaneous emission at two kinds of transitions. The equations of kinetics for the population of vibrational levels have been supplemented with additional terms representing the speeds of induced processes

$$\frac{dn_v}{dt} = R_{eV}^v + R_{VV}^v + R_{VT}^v + R_A^v + g_1^{v+1,v} I_1^{v+1,v} - g_1^{v,v-1} I_1^{v,v-1} + g_2^{v+2,v} I_2^{v+2,v} - g_2^{v,v-2} I_2^{v,v-2}, \qquad (1)$$

where R_{VV}^v, R_{VT}^v, R_{eV}^v, R_A^v are terms describing the change of population of vibrational levels during the processes of VV-exchange, VT-relaxation, electron-impact excitation, and spontaneous emission, respectively, $g_1^{v,v-1}$ and $g_2^{v,v-2}$ are the gains, $I_1^{v,v-1}$ and $I_2^{v,v-2}$ are the quantum flux densities at the fundamental frequency and at the second-harmonic frequency, respectively.

For calculating the emission spectra we use the condition of quasisteadiness

$$g_1^{v,v-1} = \Gamma_1 \qquad g_2^{v,v-2} = \Gamma_2, \qquad (2)$$

High-Temperature Institute, Academy of Sciences of the USSR, Moscow. Translated from Inzhenerno-Fizicheskii Zhurnal, Vol. 41, No. 3, pp. 514-519, September, 1981. Original article submitted June 10, 1980.

 0022-0841/81/4103-1016$07.50

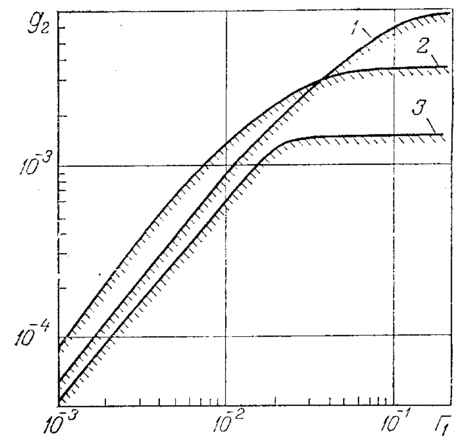

Fig. 1. Dependence of the maximum second-harmonic gain g_2 (cm^{-1}) on the threshold gain at fundamental frequency Γ_1 (cm^{-1}); 1) T = 100°K and Q = 320 J/(liter•amagat), 2) T = 200°K and Q = 320 J/(liter•amagat), 3) T = 100°K and Q = 40 J/(liter•amagat); CO:Ar = 1:10, n = 0.45 amagat, τ_p = 30 μsec.

where Γ_1 and Γ_2 are the threshold gains at the fundamental frequency and at the second-harmonic frequency, respectively. For determining the emission intensity, we differentiate these equalities and insert into them dn_v/dt from the equations of kinetics, which yields the system of equations

$$a_1^v I_1^{v+1,v} + b_1^v I_1^{v,v-1} + c_1^v I_1^{v-1,v-2} = w_1^v, \tag{3}$$

$$a_2^v I_2^{v+3,v+1} + b_2^v I_2^{v+1,v-1} + c_2^v I_2^{v-1,v-3} = w_2^v, \tag{3a}$$

where a_1^v, ..., w_1^v, a_2^v, ..., w_2^v are known functions not shown here in explicit form because of their unwieldiness. Equations (3a) are subdivided into two subsystems relative to $I_2^{v,v-2}$ for even and odd values of v, respectively. A numerical solution of Eqs. (3) yields the emission spectrum, on the assumption that emission at each vibrational transition occurs at the rotational component J with the maximum gain. These equations have been solved simultaneously with the equations of heat balance for the temperature of the gas.

Since emission at the fundamental frequency affects the gain at the second-harmonic frequency, there is a need to analyze this problem quantitatively. For this purpose, these equations were solved for various values of the threshold gain Γ_1, assuming no emission at the second-harmonic frequency, whereupon the maximum (over all second-harmonic vibrational-rotational transitions) during a pumping pulse of 30 μsec duration was calculated. The results are shown in Fig. 1. Emission at the second-harmonic frequency is possible when the second-harmonic threshold gain is lower than g_2 on the graph. As gain Γ_1 increases, the range of possible gains Γ_2 first sharply increases. Then the maximum gain at the fundamental frequency drops below the threshold and g_2 ceases to depend on Γ_1. It is to be noted that at low temperatures the efficency of emission at the fundamental frequency is high and, as a consequence, the levels within the range of maximum second-harmonic amplification become strongly depleted. This causes the maximum gain g_2 to become lower at a lower temperature over a rather wide range of Γ_1, even though a lowering of the temperature during partial inversion under otherwise the same conditions contributes to a much larger amplification.

The duration of the process to reach a quasisteady population, after the pumping has started, is known [7] to be $n_v \sim v$. The maximum amplification under typical lasing conditions occurs at the fundamental frequency at energy levels v = 5-7 and at the second-harmonic frequency at energy levels v = 15-25. Therefore, emission will begin earlier at the fundamental frequency than at the second-harmonic frequency, even when the fundamental-frequency threshold is exceeded by a relatively small amount. Only near the fundamental-frequency threshold will emission at the second-harmonic frequency begin earlier. The time in which the second harmonic reaches its maximum intensity is, however, much longer. All this is clearly depicted in Fig. 2, showing the variation of resultant emission intensities in time. The momentary small rise of second-harmonic intensity after pumping has started is caused by a

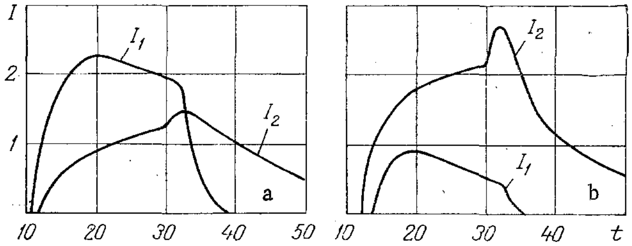

Fig. 2. Intensity of emission at the fundamental transition I_1 (kW/cm^3) and at the second harmonic I_2 (kW/cm^3): (a) $\Gamma_1 = 8\cdot10^{-2}$ cm^{-1}; (b) $\Gamma_1 = 11\cdot10^{-2}$ cm^{-1} and $\Gamma_2 = 10^{-3}$ cm^{-1}; T = 100°K, Q = 300 J/(liter•amagat), CO:Ar = 1:10, n = 0.45 amagat, τ_p = 30 μsec; time t (μsec).

small increase of the ratio of level populations n_V/n_{V-2} in the short-wave range of the spectrum during cessation of emission at the fundamental frequency, with an attendant increase of amplification and correspondingly of the emission intensity. The more the fundamental-frequency emission threhold is exceeded, the less pronounced will be this effect.

The emission spectrum integrated over the pulse duration is shown in Fig. 3a. Several rotational lines at one vibrational transition appear as a result of an interchange of emission lines, caused by heating of the gas, during the duration of a pulse. The emission spectrum in a supersonic stream of a preexcited gas, measured in an experiment [2], is shown in Fig. 3b. Despite the substantial differences between theoretical assumptions and experimental conditions, the spectra are qualitatively alike. The agreement is especially striking, if one considers that neither the threshold gain nor the degree of excitation of the gas and the temperature of the gas within the emission range can be determined from those experimental data [2] and yet the locations of the rotational lines in the spectrum as well as of the long-wave edge and of the short-wave edge depend on these parameters.

The location of the shortwave edge and of the peak of the spectrum, both depending on the initial temperature of the gas, is shown in Fig. 4a. Both correspond to higher levels when emission occurs simultaneously at two kinds of transitions than when it occurs at second-harmonic transitions only, and the levels become higher as the efficiency of emission at the fundamental frequency increases, as is the case at low temperatures. On the whole, a rising of the temperature causes the spectrum to shift toward higher levels. It must also be noted that at the fundamental frequency the entire spectrum is lumped within a narrow range about the amplification peak, while at the second-harmonic frequency the spectrum is spread over more transitions, the upper levels of the long-wage edge at the fundamental frequency being the same as the upper levels of the shortwave range at the second-harmonic frequency. The same conclusion, qualitatively, can be arrived at on the basis of the experimental data. The differences in the width of the spectra corresponding to both kinds of transitions are determined by the different way in which the gain varies over vibrational transitions. Amplification at the fundamental frequency peaks near the beginning of the plateau of the function which characterizes the population distribution over vibrational levels, but at the second-harmonic frequency it continues to smoothly increase with higher levels up to levels corresponding to maximum values of the Einstein coefficient and then begins to slowly decrease [1].

Let us now examine the energy characteristics of emission. The graph in Fig. 4b shows how the efficiency of conversion of pumping energy to radiation depends on the temperature of the gas (the conversion efficiency differs from the emission efficiency in that the latter also includes the resonator efficiency, equal to the ratio of losses associated with emission to total losses in the resonator). The dash line here refers to emission at the second-harmonic frequency only, the solid lines refer to simultaneous emission at two kinds of transitions. The strong temperature dependence of the conversion efficiency at the fundamental frequency is attributable to the high value of the threshold gain used in the calculations. The emission threshold at the fundamental frequency is not reached at a high temperature, because the gain decreases with rising temperature. During emission at the second-harmonic frequency only, the conversion efficiency decreases with rising temperature.

On the other hand, the conversion efficiency decreases also as the emission efficiency at the fundamental frequency increases with dropping temperature. There exists an optimum

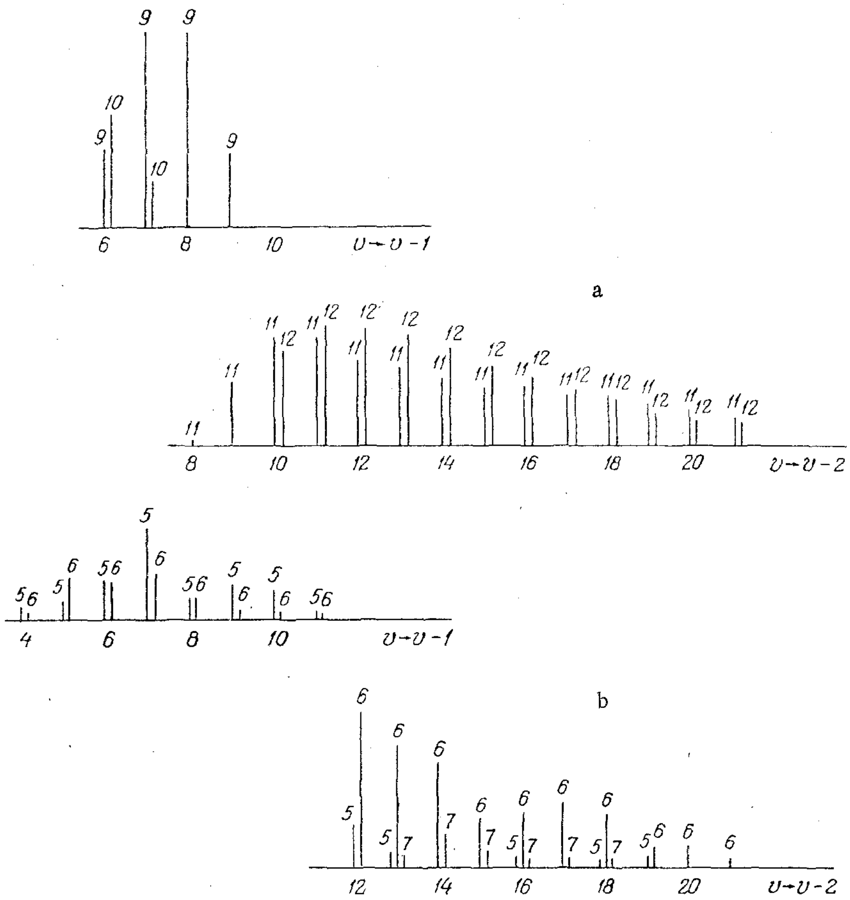

Fig. 3. Emission spectra: (a) theoretically calculated ($\Gamma_1 = 8\cdot10^{-2}$ cm^{-1}, $\Gamma_2 = 10^{-3}$ cm^{-1}, T = 100°K, Q = 200 J/(liter•amagat), CO:Ar = 1:10, n = 0.45 amagat, τ_p = 30 μsec); (b) experimentally measured [2].

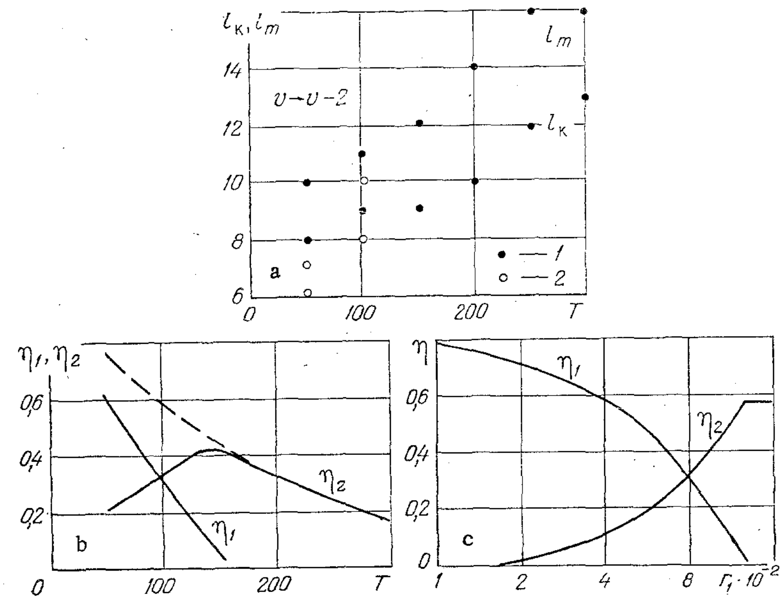

Fig. 4. Characteristics of simultaneous emission at two kinds of transitions: (a) dependence of the location of the shortwave edge of the emission spectrum (l_{sh}) and of the maximum intensity (l_m) on the temperature of the gas: 1) $\Gamma_1 = 8\cdot10^{-2}$ cm^{-1}, 2) $\Gamma_1 > g_{1,max}$; (b) dependence of the efficiency of conversion at the fundamental (η_1) and at the second-harmonic frequency (η_2) on the temperature of the gas (T, °K), $\Gamma_1 = 8\cdot10^{-2}$ cm^{-1}; (c) dependence of the efficiency of conversion of two kinds of transitions on the threshold gain at the fundamental frequency ($\Gamma_1\cdot10^{-2}$, cm^{-1}) under conditions as those depicted in Fig. 2.

temperature from the standpoint of energy-to-radiation conversion at second-harmonic wavelengths, this temperature lying near the point at which the gain at the fundamental frequency is equal to the threshold gain. This is a rather obvious conclusion, and the data in Fig. 4b as well as those in Fig. 4c depicting the dependence of the conversion efficiency on the threshold gain at the fundamental frequency provide a good basis for estimating the effect of emission at the fundamental frequency on the energy characteristics of emission at the second-harmonic frequency. As has been said before, the emission spectra corresponding to transitions of two kinds are spread over various groups of levels and those within the range of emission at the second-harmonic frequency are, moveover, located higher within the plateau of the population distribution function. Within this plateau there predominates a flow of energy toward higher energy levels. Because of that, emission at the second-harmonic frequency has almost no effect on the characteristics of emission at the fundamental frequency and can be efficient only when the gain at the fundamental frequency is sufficiently close to the threshold gain. The Q-factor of the resonator at the second-harmonic frequency must be more than one order of magnitude higher than its Q-factor at the fundamental frequency.

Our analysis indicates that, by pulse-discharge pumping, it is possible to attain experimental conditions under which emission at the second-harmonic frequency can be quite efficient.

LITERATURE CITED

1. Yu. B. Konev, I. V. Kochetov, A. K. Kurnosov, and V. G. Pevgov, "Feasibility of emission at harmonic frequencies by molecules of carbon oxide with pumping in electric discharge," Pis'ma Zh. Tekh. Fiz., 3, No. 23, 1267-1271 (1977).
2. R. C. Bergman and J. W. Rich, "Overtone-bands lasing at 2.7-3.1 μm in electrically excited CO," Appl. Phys. Lett., 31, 597-799 (1977).
3. N. G. Basov, V. A. Danilychev, A. A. Ionin, V. S. Kazakevich, and I. B. Kovsh, "Cooled electroionization laser on two-quantum transitions in the CO-molecule," Kvantovaya Elektron., 5, No. 8, 1855-1857 (1978).
4. A. F. Suchkov and Yu. N. Shebeko, "Theoretical study of energy and spectral characteristics of a laser at the second harmonic of a CO-molecule," Kvantovaya Elektronika, 6, No. 5, 960-964 (1979).
5. Yu. B. Konev, I. V. Kochetov, V. G. Pevgov, and V. F. Sharkov, "Analysis of kinetic processes which determine the performance parameters of CO-lasers," Preprint Institute of Atomic Energy, 2821 (1977).
6. Yu. B. Konev, I. V. Kochetov, and V. G. Pevgov, "Characteristics of a pulsed CO-laser," Zh. Tekh. Fiz., 49, 1266-1272 (1979).
7. S. A. Zhdanok, A. P. Napartovich, and A. N. Starostin, "Establishment of the distribution of diatomic molecules over vibrational levels," Zh. Eksp. Teor. Fiz., 76, 130-139 (1979).