Spectral characteristics of Q-switched CO laser

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Abstract: The spectrum of low-pressure cryogenic CO laser operated in Q-switched mode was measured at frequencies of 70 Hz and 120 Hz. CO laser spectrum consisted of 115 spectral lines in the wavelength range from 4.89 μm to 6.54 μm at 70 Hz, and 102 lines in the wavelength range from 4.90 μm to 6.44 μm at 120 Hz. For the first time the dynamics of generation on each spectral line for full CO laser spectrum were measured. We identified rotational-vibrational transitions and analyzed the processes, which affect the formation of the CO laser spectrum. This data were taken into account to determine the peak powers of all the spectral lines correctly.

1. Introduction

Research and development of the mid-IR laser source has of great interest for solving many problems of gas analysis, laser chemistry, medicine, isotope separation, and a number of others. For example, many molecules, including pollutants, explosives and toxic substances have absorption lines in this spectral range, and the absorption of human body tissues strongly depends on the wavelength [1].

One of the most effective sources of laser radiation in mid-IR is CO laser. This laser can generate radiation on hundreds of vibrational-rotational lines. The lower vibrational levels of the CO molecule are excited by the electric discharge, and the upper vibrational levels are populated by the vibrational-vibrational exchange due to collisions between anharmonic CO molecules. Thus, a partial inversion population is created on a large number of vibrational-rotational transitions, and due to the cascade mechanism a large number of spectral lines are generated in a wide range of wavelengths [2]. The number of these lines can reach many hundreds [2] for the fundamental vibrational bands in the wavelength range from 4.6 μm [3] to 8.7 μm [4] and the first vibrational overtone in the wavelength range from 2.5 μm to 4.2 μm [5].

The existence of a cascade mechanism of generation leads to the fact that the CO laser has the highest efficiency among gas-discharge lasers. Output efficiency of fundamental band CO lasers is ~50% [2], first-overtone CO laser efficiency is 16% [6].

However, spectral gap, in which CO laser does not emit, is required for a certain application. One method of expanding and enriching the spectrum of a CO laser is the frequency conversion of the radiation in nonlinear crystals. At the present time sum-frequency conversion of radiation in ZnGeP$_2$ [7], AgGaSe$_2$ [8], GaSe [9], and PbIn$_6$Te$_{10}$ [10] with an internal conversion coefficient of
6.5%, 1%, 0.3% and 0.01%, respectively, was realized. In order to do this, it is necessary to have a high peak power of radiation, for example, we can use Q-switch laser to achieve this. Actually, the conversion efficiency of broadband CO-laser radiation depends both on the characteristics of used nonlinear crystals and on the characteristics of the CO laser itself.

The purpose of this work is a detailed investigation of the spectral-temporal characteristics of a Q-switched cryogenic CO laser pumped by a direct current discharge. Previously, the spectral-temporal characteristics of such laser were investigated both experimentally and theoretically in [11-12]. Although limited experimental results were given in these publications, but they showed that the generation time on separate vibrational-rotational lines is very different.

2. Experiment Set-up
We used Q-switched CO laser for investigating the dynamics of generation on individual vibrational-rotational lines. The optical scheme of our experiment is presented in figure 1. The ends of the CO laser tube 1 were coated with Brewster windows, which are made of CaF₂. The gas mixture of active medium 1 consisted of He:N₂:CO:Air=70:5:1:1. Tube voltage was 9 kV and a current was 6 mA. The pressure of the mixture was 7.7 Torr.

![Figure 1. Optical scheme. 1 – CO laser tube; 2 – totally reflective spherical mirror; 3 – partially reflective mirror; 4 – rotating mirror; 5 – diaphragm; 6, 10 – CaF₂ flat plates; 7, 13, – spherical mirrors; 8 – power meters; 9, 15 – photodetectors; 11, 12 – turning mirrors, 14 – spectrometer IKS-31.](image)

The laser resonator was formed by a reflective spherical mirror 2 (radius of curvature R = 9 m) and a flat output mirror (reflection coefficient ≥90% in the wavelength range ~ 5.0-6.5 μm). A flat rotating mirror 4 was placed inside the resonator, thus the laser operated in Q-switch mode. Diaphragm 5 provided operation of the laser on the fundamental transverse mode. To control the average power of radiation, its part (~ 5%) was directed to a spherical mirror 7 (R = 0.6 m) by a plane-parallel plate 6 of CaF₂. Further, the radiation was focused on a power meter 8 (Ophir-10A), and a photodetector 9 (PEM-L-3, temporal resolution 0.5 ns) by another plate 10 of CaF₂ to control the temporal shape of the total spectrum pulse.

The main part of the radiation (~ 95%) was directed by turning mirrors 11 and 12, and spherical mirror 13 (R = 0.5 m) into the spectrometer 14 (IKS-31) for measuring the spectral characteristics. The selected radiation was directed to the photodetector 15 (PEM-L-3). Signals from photodetectors 9 and 15 were recorded on an oscilloscope Tektronix TDS 1012 (not shown in figure 1).

3. Dynamics of generation of selected spectral lines
A typical oscillogram, which was recorded on an oscilloscope, is presented in figure 2. Signal 1 corresponds to the dynamics of the generation of the total spectrum CO laser pulse, and signal 2 corresponds to the dynamics of generation on a particular vibrational-rotational line. The results were
averaged over 4 measurements. Generation durations of 0.1 and 0.5 power level on a particular vibrational-rotational line are shown in blue and red lines, respectively.

The dynamics of generation of the total pulse and individual rotational components of the vibrational band 7-6 is presented in figure 3. One can see from the figure that the strongest lines, for example, P(9) and P(8) completely overlap in time. Consequently, they will interact within a nonlinear crystal and sum-frequency generation occurs the most effectively. There are lines, for example, P(8) and P(11), which partially overlap in time. Consequently, sum-frequency generation occurs less effectively in this case. But there are also such lines, for example, P(7) and P(12), which practically do not overlap in time. It means that sum-frequency generation of these lines doesn’t occur at all.

Figure 2. A typical oscillogram of generation dynamics of the total spectrum pulse (1), and the dynamics of generation of a specific vibrational-rotational line (2).

Durations of spectral lines generations for Q-switching frequencies of 70 Hz and 120 Hz depending on the wavelength is presented in figure 4. The blue segment shows the duration of the level of 0.1, and the red one shows the duration of the level of 0.5 from the maximum of the pulse. Also, the points indicate the moments when the pulse generation on the each line reached its maximum. In the upper part of figure 4, the horizontal segments show the wavelength ranges corresponding to the vibrational band, the transitions of which are indicated: (V+1) – V P(J), where V is the vibrational quantum number, and J is the rotational quantum number. The generation time at the level of 0.1 at Q-switching frequency of 70 Hz is approximately twice as long the generation time at Q-switching frequency of 120 Hz. It is seen, when vibrational bands are low (V = 3–13), laser generation begin at low and medium rotational components (J = 6–10). Whereas the generation at higher rotational components (J = 11–13) of each vibrational band began in the second half of the entire laser pulse. In general, we can observe that with an increase of the number of the rotational component within a single band the moment of reaching the maximum power is observed at a later time. In middle vibrational bands (V = 14–23) this analysis was difficult due to a decrease of rotational components. This is apparently due both to a gain decrease of these lines and to the presence of air absorption in this spectral range (5.6–6.5 μm).
Figure 4. Duration of spectral lines generation for Q-switching frequencies of 70 Hz (a) and 120 Hz (b).

We can observe that the generation at the lowest vibrational band \((V = 3)\) began with a significant delay when compared with generation on higher vibrational bands. It can be concluded that the population inversion in this vibrational transition appears only due to the "falling" of CO molecules from higher levels by generation on higher vibrational bands. In this case, clear advantage of the multilevel generation of CO laser is the cascade mechanism of the appearance of a population inversion.

4. Method of calculating the generation peak power of spectral lines and the generation spectrum

The radiation power of individual vibrational-rotational lines was measured in relative units (Volts). The maximum value in these units for each line was multiplied by the generation time for a given line in the level of 0.5. Thus, the generation energy of a given line was obtained in relative units. The sum of the energies over all the lines gave the energy of the generation pulse, which is total in the spectrum, in relative units. Conversion of peak power to Watts in this work was carried out by normalizing the total generation pulse to the real energy. The single pulse energy is equal to the average power of the total radiation (actually measured in the experiment) divided by the Q-switching frequency.

Then the peak power of the spectral lines was refined by the spectral response of the photodetector. According to the dependence, which is known from the photodetector's passport, the actual power of CO laser was calculated.
Peak power of the majority of the lines obtained using this method is 20% higher than the power calculated from the simplified method. It was assumed that all the generation lines have the same duration at the level 0.5, and its equal to the duration of the total pulse in the spectrum.

The power distribution along the generation lines and the identification of vibrational-rotational transitions for a Q-switched multi-line CO laser are shown in figure 5. The spectrum also indicates vibrational-rotational transition titles.

The obtained spectrum of a CO laser at a Q-switching frequency of 70 Hz consisted of 115 lines in the wavelength range from 4.89 μm to 6.54 μm. The spectrum of a CO laser at a Q-switching frequency of 120 Hz consisted of 102 lines in the wavelength range from 4.90 to 6.44 microns. In both cases, the strongest lines were observed in the wavelength range from 4.8 to 5.3 μm. The maximum peak power is on the transition 8 - 7 P (9). In each of the vibrational bands, the rotational components with J = 9\(\div\)12 were the strongest.

![CO laser spectrum at a Q-switching frequency of 70 Hz.](image)

Figure 5. CO laser spectrum at a Q-switching frequency of 70 Hz.

Figure 6 presents that the spectral lines are only in those ranges of wavelengths where the air absorption is not very large. Transmission value is indicated by a border between yellow and white.
Figure 6. Part of the CO laser spectrum at Q-switching frequency of 120 Hz and the air transmittance.

5. Conclusions
As a result of experiments, the generation of the Q-switched multi-line CO laser spectrum at two different frequencies was obtained. For the first time, the dynamics of the generation of such CO laser on all lines of the spectrum was measured. When Q-switching frequency was 70 Hz the spectrum consisted of 115 spectral lines in the range from 4.89 μm to 6.54 μm. When it was 120 Hz 102 lines were obtained in the wavelength range from 4.90 μm to 6.44 μm. The peak powers of the spectral lines were calculated with normalization for the duration of their generation at a level of 0.5. We identified transitions, which produce every line, and analyzed the processes, which affect the formation of the spectrum.

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6. References
[1] Rodin A V, Borisov V M, Kuz'min V N and Mezhevov V S 2004 Pulsed lasers operating from UV to IR at TRINITI for possible medical applications Proc. of SPIE 5486 374
[2] Ionin A A 2007 Electric discharge CO laser Gas Lasers ed M Endo and R Walter (Boca Raton: CRC Press) pp 201-238
[3] McCord J E, Ionin A A, Phipps S P, et al. 2000 IEEE Journal of Quantum Electronics 36 1041
[4] Ionin A A, Kinyaevskiy I O, Klimachev Yu M, et al. 2017 Optics letters 42 498
[5] Basov N G, Hager G D, Ionin A A, et al. 2000 Efficient pulsed first-overtone CO laser operating within the spectral range of 2.5-4.2 μm IEEE J. Quantum Electronics 36 810
[6] Ionin A A, Klimachev Yu M, Kozlov A Yu, et al. 2006 Quantum Electronics 36 1153
[7] Andreev Yu M, Ionin A A, Kinyaevskiy I O, et al. 2013 Quantum Electronics 43 139
[8] Budilova O V, Ionin A A, Kinyaevskiy I O, et al. 2016 Optics Letters 41 777
[9] Lai-ming Zh, Ji-Jiang X, Jin G et al 2012 Optics and Precision Engineering 20 277
[10] Ionin A A, Kinyaevskiy I O, Klimachev Yu M, et al. 2016 Optics Letters 41 2390-93.
[11] Basiev A G, Golubev A A, Gurashvili V A and Izyumov S V 1980 Soviet Physics Technical Physics 25 1016
[12] Basiev A G, Galtsev V E, Gurashvili V A, et al. 1981 Features of the spectrum formation of Q-switched CO laser Preprint of Institute of Atomic Energy No 3448/12 (in Russian)