COMPRESSED-GAS LASERS

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Results are presented of theoretical and experimental investigations of high-power compressed-gas lasers. The electroionization method of excitation is considered, as well as pumping by an intense electron beam. Experimental data are presented on the threshold and output characteristics, the efficiencies, and the gains of CO_2 and CO lasers operating without cooling the active medium. The prospects are discussed of utilizing the electroionization method to excite lasers on electronic transitions. Results are presented of the investigations of lasers operating with compressed xenon and $Ar:N_2$ mixtures, pumped with an electron beam, in which the lasing is on the electronic transitions of molecules Xe_2 ($\lambda \simeq 172$ nm) and N_2 ($\lambda \simeq 357$ nm). Prospects of using compressed-gas lasers in the thermonuclear fusion region, for selective stimulation of chemical reactions, and for applications in the material-finishing industry are discussed.

INTRODUCTION

Interest in compressed gases as active media for lasers is due to their high homogeneity, the possibility of attaining a high concentration of the active particles, and the existence of gas-laser systems with efficiencies up to 50%. In addition, at high pressures it is possible to tune the frequency smoothly, to generate ultrashort pulses, and to obtain high radiation power and coherence. These properties of compressed gases attract attention as possible active media for high-power lasers, the need for which is being particularly strongly felt of late in connection with the development of work on controlled thermonuclear fusion, task-oriented stimulation of chemical reactions, and other laser applications.

The problem of developing powerful compressed-gas lasers is fraught with two basic difficulties. First, the traditional method of exciting gas lasers, with a self-maintaining electric discharge, cannot be used to excite sufficiently large volumes of compressed gases, because of the instabilities that occur in the discharge and which lead to pinching of the discharge and to impossibility of volume excitation. It becomes therefore necessary to develop new methods for exciting compressed gases. Second, processes of population of laser levels in compressed gases can be accompanied by an appreciable increase in the role of quenching collisions of active particles with neutral molecules and electrons. In addition, impact broadening of laser levels, which is proportional to the gas pressure, leads to the need for an additional increase of the pumping rate with increasing pressure.

To excite lasers that use working media with large concentration of active particles, a method of pumping with electron beams was proposed in 1961 [1]. The application of this method has made it possible to obtain lasing in semiconductors [2, 3] as well as condensed and compressed gases [4, 5]. The working medium was excited with the aid of large-current nanosecond accelerators, the electron current of which reached 10^4 A at electron energies 1 MeV. The development of high-power accelerators for the excitation of lasers with large working-medium volumes is a complicated technical task. In addition, the average energy of the secondary electrons produced in the interaction between the electron beam and the laser active media amounts to ~10-30 eV, so that laser pumping with an electron beam is effective for the excitation of electron transitions and is ineffective for the excitation of vibrational–rotational transitions: the maxima of the excitation cross section of the latter lie in the region of 1-2 eV. However, the excitation of the vibrational levels is of great interest, for it is precisely the vibrational–rotational molecule transitions that make possible lasing with very high efficiencies, up to 30-50% [6].

In 1970, it was proposed [7, 8] to produce free electrons with the aid of an external ionization source, thereby raising the pressure and increasing the working volume of the gas lasers.

The first compressed-gas laser was developed in 1971 at the Lebedev Physics Institute, using a mixture of carbon dioxide and nitrogen at a total pressure of 25 atm [9, 10]. The radiation power per unit volume in this laser was approximately 10^6 times larger than in an ordinary CO_2 laser.

These studies have demonstrated the following:

(a) Triple quenching collisions have little effect on the lasing characteristics of compressed-gas lasers up to a pressure of 25 atm.

(b) The excitation method is characterized by a high degree of spatial homogeneity, and the discharge does not tend to contract.

(c) At a high degree of ionization, the internal field of the plasma exerts practically no screening action on the external field and does not lead to a nonuniform utilization of the working volume and to an abrupt reduction of the laser output energy, as suggested in [7]. These were named "electroionization" lasers.

The combined excitation of gas lasers by an electric discharge and ionizing radiation was investigated earlier in a number of studies at gas pressures and active-medium volumes typical of an ordinary low-pressure gas-discharge laser, under conditions when there is no pinching (contraction) of the autonomous glow discharge. Thus, by pumping an argon laser with a plasma-beam discharge, a plasma electron temperature ~100 eV was attained in [10], and lasing was produced at very low gas pressures, $\sim 10^{-4}$ Torr. The effect of a proton beam on the generation of a gas laser based on CO_2 at pressures 1-10 Torr is the subject of the studies in [11]. In these studies, the possibility of going to higher pressures was not considered, and the experiments were performed under conditions when the pinching of the discharge did not take place, and the gas was not additionally ionized with an external source.

Attempts were made in [12] to raise the working-gas pressure. However, no appreciable increase of the pressure could be obtained in comparison with that in an ordinary gas-discharge laser: generation in a CO_2 laser with combined pumping by an electron beam and an electric discharge could not be obtained at pressures above 30 Torr.

By using various technical methods of stabilizing the glow discharge, the authors of [13, 14] succeeded in significantly raising (to ~1 atm) the pressure of the working gas in a CO_2 laser. In the lasers described in [13, 14], a transverse discharge was used (in place of the customarily employed longitudinal discharge), as well as specially shaped electrodes. These lasers were named TEA lasers. However, the use of a transverse discharge did not change in fundamental fashion the pumping mechanism, and did not make it possible to advance into the region of high pressures or to increase significantly the volume of the active medium.

Persson's work [15] on the stabilization of a glow discharge of low pressure by an electron beam served as the starting point of research aimed at finding methods of pumping atmospheric-pressure CO_2 lasers, performed at the Los Alamos laboratory in the USA. Members of this laboratory published in 1971 a communication reporting amplification in a mixture of carbon dioxide, nitrogen, and helium at atmospheric pressure, excited by a discharge stabilized with an electron beam [16]. The authors of that paper, however, were cautious in their estimates of the possibility of using the pumping method realized by them to excite an active medium at pressures higher than atmospheric.

At the present time, even though the electroionization principle of exciting dense gases is only about two years old, it is precisely with electroionization lasers that many outstanding accomplishments were made in laser technology:

1. Considerable volumes of dense gases were excited, amounting to dozens or even hundreds of liters [18].
2. Energy outputs of 50 $J\text{-}liter^{-1}\text{-}atm^{-1}$ were realized at efficiencies 25-30% [17-20].
3. It was shown that such lasers can operate at high pressures ~100 atm [21].
4. Pulsed (including pulses shorter than a nanosecond), quasi-continuous, and continuous lasing regimes of high-pressure lasers were realized [17, 22].
5. Work on tuning the lasing frequency in a wide range of frequencies is being successfully pursued [23, 24].

In spite of all these accomplishments, many questions still await their solution and are connected both with the physical processes in the active medium and with the development of the individual laser elements.

A more complete investigation of the probabilities of various elementary processes is needed. The existing information concerning, for example, the CO_2 molecule alone, which is one of the most thoroughly investigated, is insufficient even for a rough estimate of the lasing power and of the gain attained between different highly excited levels. Yet it is just these transitions which make it possible to tune the frequency of a CO_2 laser in a wide range.

A very important question is that of the effective energy pickoff under conditions when ultrashort pulses are amplified. A closely related problem is that of the nonlinear optical phenomena that arise when a light pulse propagates in the active medium. At high pressures, an essential role can be played by effects that are not linear in the pressure, by triple quenching collisions, and by the onset of new optical transitions that are induced by pressure and by the strong electric field.

The chemical transformations that occur in the plasma produced by the electroionization method are of undisputed interest, since a feature of this plasma is the large difference between the vibrational and translational temperatures and the high density of the vibrationally excited molecules. At a translational temperature close to room temperature, the temperatures of the individual vibrational degrees of the molecule can reach thousands of degrees. Chemical reactions occurring under such thermodynamic disequilibrium conditions have very high rates, consume little energy, and produce a high yield of end products [25]. Some of the chemical reactions that occur in an electroionization plasma are of independent practical interest.

We have mentioned only some of the questions that are raised when more attention is paid to high-pressure gas lasers. It is seen, however, even from this short list that a large number of new physical problems must be solved if high-pressure gas lasers are to become practical. Some of them will be discussed in the present article.