

S. A. Losev

Gasdynamic Laser

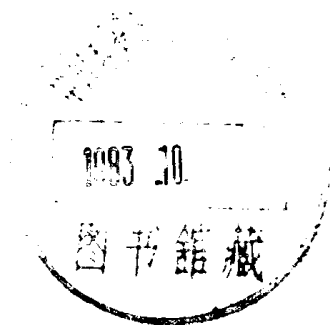
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S. A. Losev

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With 100 Figures



5506387

Springer-Verlag Berlin Heidelberg New York 1981

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Title of the original Russian edition:

Gazodinamicheskie lazery

© by "Nauka" Publishing House, Moscow 1977

2121001-4

ISBN 3-540-10503-4 Springer-Verlag Berlin Heidelberg New York
ISBN 0-387-10503-4 Springer-Verlag New York Heidelberg Berlin

Library of Congress Cataloging in Publication Data. Losev, S. A. (Stalii Andreevich). Gasdynamic laser. (Springer Series in Chemical Physics ; v. 12) Translation of Gazodinamicheskie lazery. Bibliography: p. Includes index. I. Gasdynamic lasers. I. Title. II. Series. TA1695.L6713 621.36'63 81-1574 AACR2

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Printed in Germany

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Offset printing: Beltz Offsetdruck, Hemsbach/Bergstr. Bookbinding: J. Schäfer oHG, Grünstadt.
2153/3130/543210

Preface

This book deals with gasdynamic lasers (GDL)—high-energy sources of coherent directional radiation. The theory and practice of gasdynamic lasers are based on three fields of modern science: quantum electronics, physico-chemical kinetics, and gasdynamics. This circumstance has determined the content of this book, which can be divided into two parts. The first four chapters, which occupy a considerable part of the book, prepare the reader for discussing the theoretical and experimental results of up-to-date GDL studies. The necessity of such a presentation is dictated by the fact that gasdynamic lasers can be a subject of interest for readers who are experts in only one of the mentioned fields, or those who have just begun studying GDLs. Such a representation is based on the experience gained by the author over several years in delivering lectures on this subject to students of Moscow State University. These lectures formed the basis of the book, which can also be used as a text.

The basic information on gasdynamic lasers is contained in the last two chapters of the book. These chapters give mathematical models of processes occurring in existing high-energy infrared GDLs (CO_2 GDLs, carbon monoxide GDLs, etc.), experimental results for these lasers, and also consider some possible new designs of GDLs. Of greatest interest in this respect are the attempts to create recombination electronic GDLs and plasmadynamic lasers.

The number of studies devoted to the development of high-energy GDLs is continuously increasing. Several reviews on this subject have been published. The first monograph about gasdynamic lasers, the book by Anderson, which was published in the USA in 1976, is a very good introduction to the field. A year later our book, with an extensive bibliography of the work of Soviet scientists, was published in the USSR.

In preparing the present English edition of the book we have taken into account recent advances in the development of gasdynamic lasers. In particular a new section devoted to GDLs on twin modes of the CO_2 molecule

vibrations was added. We also omitted the references to papers not easily accessible to English readers but retained the English references. Most of the Soviet scientific journals and books are published in the USA in English translation. In those cases where the author had no information about the availability of a translation, the original Russian references are given.

The author wishes to give special acknowledgement to his colleagues N.A. Fomin, A.I. Demin, N.V. Evtyukhin, V.K. Konyukhov, G.A. Lukyanov, V.A. Kochelap, and V.A. Khokhryakov, who helped him greatly in preparing the English translation of the book. The author also gives thanks to the translator N.V. Deineko, who worked laboriously to present this book in English. We both hope that this work will be helpful and will contribute to better understanding between scientists of different countries.

Moscow, January 1981

S.A. Iosev

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1. Introduction

In a gasdynamic laser (GDL), radiation is produced by rapidly cooling a preheated gas. This can be achieved by accelerating the gas to supersonic velocities. However, not every laser with a rapidly moving working medium can be called a gasdynamic laser. The utilization of moving gases in electric-discharge lasers and other types of lasers have made it possible to increase the output power considerably but have not altered the basic principle of creating an active medium. The specific feature of gasdynamic lasers considered in this book is that the laser effect results from the motion of a gas that leads to a disturbance of thermal equilibrium in the system and creates the population inversion of energy levels in gas molecules. Thus, gasdynamic lasers are devices in which thermal energy is directly transformed into coherent directional radiation.

At present most high-power gasdynamic lasers operate in the infrared spectral region on optical transitions between vibrational energy levels of CO_2 molecules. Carbon monoxide, nitrous oxide, and carbon sulphide lasers have also been developed. Attempts are being made to create high-power GDLs operating in other spectral regions—visible and ultraviolet, that is, employing transitions between electronic energy levels of atoms and molecules.

A schematic diagram of a gasdynamic laser is given in Fig.1.1. Preheated working gas is delivered to a nozzle where it is accelerated and cooled. During rapid cooling, the different deactivation rates of molecules possessing different energies lead to a population inversion of energy levels and the concentration of more highly excited molecules exceeds the concentration of less highly excited molecules. Then the gas enters a cavity, which consists of two mirrors (one of them is semitransparent) parallel to the flow. In the cavity, a part of the energy associated with population inversion is transformed into directional coherent radiation that passes through the semitransparent mirror, to form a laser beam.

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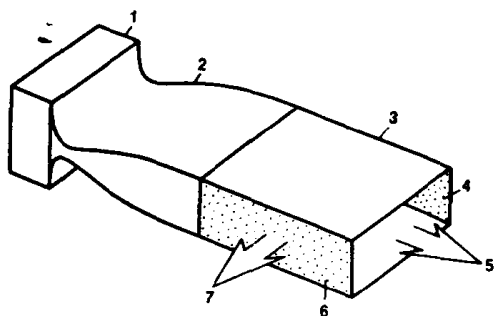


Fig.1.1. Schematic of a gasdynamic laser. (1) heater; (2) nozzle; (3) cavity; (4) reflecting mirror; (5) gas flow; (6) semitransparent mirror; (7) output laser beam

The development of gasdynamic lasers has begun quite recently. Several reviews have been published [1.1], and the monograph by ANDERSON [1.2] is a very good introduction to the field. But before considering the subject matter of the book let us mention some historical background which shows the development of ideas underlying the gasdynamic laser concept.

First works suggesting that thermal excitation of a quantum system could be used to produce coherent electromagnetic radiation appeared in 1959-1963 [1.3]. These works considered a three-level system with different rates of establishing thermal equilibrium, in which population inversion formed during cooling. In [1.4] an analysis of a concrete scheme of obtaining population inversion of energy levels of CO_2 molecules by creating a temperature gradient in a gas contained between hot and cold walls was given. In [1.5] the authors put forward an idea of possible population inversion of electronic energy levels during rapid cooling of a gas in a supersonic nozzle. The authors of [1.6] suggested that cooling a plasma can also serve as a GDL active medium.

The possibility of a considerable distortion of local thermodynamic equilibrium in a rapidly accelerated gas, accompanied by its heating (during compression) or cooling (during expansion), is well known in gas dynamics (see [1.7,8]). Among the first experiments in which a delay of deactivation of vibrational degrees of freedom of molecules was observed were [1.9] (CO_2 cooling in a flow) and [1.10] (nitrogen flow in a nozzle of a shock tube). On the other hand, still earlier in [1.11] a highly effective energy transfer from nitrogen to CO_2 molecules was observed in an electric discharge. In [1.12,13] this phenomenon was used for the first time for selective excitation of the upper laser level in creating a CO_2 electric-discharge laser (see [1.14]).

The first proposal for creating an infrared gasdynamic laser operating on a $\text{CO}_2\text{-N}_2$ mixture with supersonic nozzle cooling appeared in 1966 [1.15,16].

In [1.17,18] the authors considered the possibility and methods of thermal pumping of vibrational energy levels of polyatomic molecules. In [1.19] it was suggested that carbon monoxide burning should be utilized to obtain excited CO_2 molecules and to create population inversion during subsequent cooling.

Operating conditions of GDLs were experimentally studied in [1.20]. At last, in 1970 first reports about CO_2 gasdynamic laser performance appeared. Experiments were repeated using shock tubes with nozzles [1.21-23], continuously operating setups with electrical heating at a nozzle entrance [1.24], with fuel mixtures [1.22], and then, in 1971, using detonation of solid explosives [1.25]. Subsequently many other reports about not only CO_2 GDLs but also carbon monoxide GDLs (first in [1.26]), nitrous oxide (first reports [1.27,28]), and carbon sulphide [1.29,30] GDLs appeared. The population inversion of electronic energy levels of hydrogen atoms was first obtained in [1.31] in a cooling plasma jet.

To date gasdynamic lasers provide 20 to 25 J of coherent radiation energy per gram of a working gas [1.32,33] (in [1.34] a specific power of 50 J per gram of nitrogen was reported). This is inferior to specific power output from rapid-flow electric-discharge or chemical lasers. The GDL efficiency, about 1%, is also low so far. This, however, does not narrow the prospects of gasdynamic lasers, since these devices provide a direct conversion of thermal energy into the energy of a laser beam.

Advantages of gasdynamic lasers become especially noticeable in creating continuously operating high-power lasers, since the efficiency of these devices grows with a scale of a setup due to the decrease of heat losses. It should be noted that the development of high-power chemical lasers is complicated because of high toxicity and chemical activity of their working mixtures. An important advantage of gasdynamic lasers, especially of CO_2 lasers, is the possibility of obtaining laser radiation using combustion products of common fuels, which greatly increases their field of application.

High-power continuously operating GDLs will eventually have a great impact on many fields of science and technology. For example, lasers can be utilized in high-quality processing (deep welding, precision cutting, heating, spraying, and so on), in the development of a new trend in laser chemistry and chemical technology (selective control of chemical reactions, in particular isotope separation and obtaining perfectly pure substances), in wireless transmission of high energy over large distances (to orbital

stations, spacecraft, and so on) and in weather control (elimination of mist and clouds in airport zones). The development of high-power industrial lasers has begun quite recently, and they have many applications. The role of gasdynamic lasers in this respect may turn out to be very significant.

In the present book we consider mainly the theoretical foundations of gasdynamic lasers. In this respect the book has a somewhat wider scope than the known monograph by ANDERSON [1.2]. However, this shouldn't discourage an unprepared reader since we start from a simple presentation of the fundamentals of those branches of science which are required for the development of gasdynamic lasers and which are quite comprehensible for a wide circle of readers including theoreticians and experimenters. These are quantum electronics, physico-chemical kinetics, and gas dynamics. The next three chapters of the book deal with these fields and contain the information and examples required for understanding the theory of gasdynamic lasers. If the reader has a desire to go deeper in these fields of science, we refer him to the textbooks and monographs contained in References.

Chapter 5 is the main part of the book as it gives the concept of the infrared CO_2 gasdynamic laser—the most widespread type of lasers which has already found practical applications in technology. Other types of gasdynamic lasers are described in Chap. 6. The most interesting here are the promising developments of high-power gasdynamic lasers for a visible and ultraviolet spectral regions.

The main problem considered in this book is that of obtaining an active medium by gasdynamic methods and describing its properties using various mathematical models. The technical problems concerning the creation of gasdynamic lasers (for example, the development of heaters, combustion chambers, high-power optical cavities, and diffusers) are beyond the scope of the book and are considered in detail in references. Therefore, this book cannot be regarded as a manual for the designers, although it is impossible to develop a gasdynamic laser without understanding the theoretical principles of its operation.

So, let's start!

2. Basic Concepts of Quantum Electronics

This chapter considers the rotation and vibration of molecules. The concepts of spontaneous and induced transitions and the Einstein coefficients determining the optical transition probability are introduced along with a description of spectral line contours in a gas and the mechanism of line broadening. Introductions to the concepts of light absorption and amplification coefficients in a gas, the population inversion of energy levels and pumping are given. Building on these principles the creation of population inversion in gasdynamic lasers is then discussed. The chapter continues with a discussion of resonator performance, in which laser radiation is generated; threshold conditions for generation and types of losses; and the concepts of useful radiation power and resonator efficiency. The problem of radiation extraction from a cavity, and the formation of a directed beam are also discussed and various types of resonators (stable and unstable) and multipass amplifiers are considered. The chapter concludes with a consideration of the problem of a rapid active medium flow in a cavity, losses due to gas inhomogeneities, and the presence of condensed particles in a flow.

2.1 Energy Levels and Quantum Transitions in Atoms and Molecules

Quantum electronics, which is a specific combination of atomic and molecular physics and optics, actually appeared about twenty-five years ago. It has, however, an earlier history that is closely related to the development of 20th century physics, specifically the combination of ideas concerning the wave and corpuscular nature of matter known as quantum mechanics. In 1954 Basov and Prokhorov in the Soviet Union and Townes in the USA created the first lasers— NH_3 molecular generators of radiation at about 1 cm wavelength. The first ruby laser operating in the optical range was developed in 1960, and the first gas lasers were reported in 1961¹. (Footnote see next page.)

Quantum electronics studies processes occurring in atoms and molecules. Apart from translational motion of a molecule as a whole, the simplest motion of a molecule is its rotation. To a first approximation the rotation is described by the model of a *rigid rotator*. The quantization of its rotational energy yields

$$E_{\text{rot}}(J) = (h^2/8\pi^2 I)J(J+1) \quad , \quad (2.1.1)$$

where h is Planck's constant, I is the moment of inertia of a molecule, and J is the rotational quantum number. The separation of rotational energy levels $E_{\text{rot}}(J)$ increases with J .

To describe vibrations of atoms in a molecule the concept of the *harmonic oscillator* is used, in which an elastic force, returning the system to equilibrium, is proportional to the amplitude of deflection. The potential energy of a harmonic oscillator is (Fig.2.1a)

$$U = k(r - r_e)^2/2 \quad , \quad (2.1.2)$$

where r is the distance between nuclei in a molecule and r_e is that distance at equilibrium.

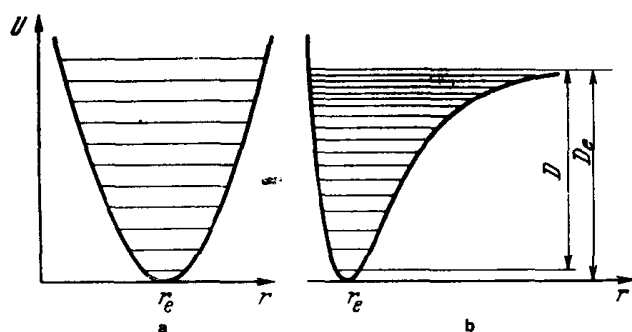


Fig.2.1a,b. Potential energy curves for a harmonic oscillator (a) and a Morse anharmonic oscillator (b). D is the energy of dissociation

Quantum mechanics permits for a harmonic oscillator (2.1.2) only those states in which its energy is

$$E_{\text{vib}}(v) = h\nu_0(v + 1/2) \quad , \quad v = 0, 1, 2, \dots \quad , \quad (2.1.3)$$

where ν_0 is the fundamental frequency of vibrations. Energy levels in a harmonic oscillator are equidistant. This model is a good approximation to re-

1 Fundamentals of quantum electronics and laser physics are given in detail in [1.14, 2.1-4].

ality when amplitudes of vibrations of atoms in a molecule are small. In the next approximation we must account for the anharmonicity of vibrations using, for example, the *Morse oscillator* model (Fig.2.1b),

$$U = D_e \{1 - \exp[-\alpha(r - r_e)]\}^2, \quad (2.1.4)$$

where D_e is the potential well depth and α is a parameter related to the frequency of vibrations and D_e . The limit at $r \rightarrow \infty$ corresponds to dissociation of a molecule. The expression for energy levels of the Morse oscillator corresponding to potential (2.1.4) is

$$E_{\text{vib}}(v) = h\nu_0(v + 1/2) - (h^2\nu_0^2/4D_e)(v + 1/2)^2, \quad (2.1.5)$$

where ν_0 is the fundamental frequency of vibrations of the respective harmonic oscillator. From (2.1.5) it is clear that for (2.1.4) energy levels get closer as v increases.

The motion of electrons in fields of nuclei of atoms and molecules is described by more complicated equations. The potentials of this type of motion and the respective energy levels E_e are given, for example, in [2.5-7].

The spacing of vibrational energy levels, ΔE_{vib} , is usually much greater than the spacing of rotational energy levels, ΔE_{rot} , and in turn $\Delta E_{\text{vib}} \ll \Delta E_e$. For this reason we say that to every electronic state of a molecule there corresponds a system of vibrational levels, and to each of these levels, a system of rotational levels.

Sometimes for one value of energy there can be two or more states of a system, which are indistinguishable for macroscopic observations in ordinary conditions. Deformation (bending) vibrations of a linear CO_2 molecule can serve as an example (Fig.2.2). Here two independent directions of vibrations at the same frequency correspond to one value of vibrational energy. One of these vibrations proceeds in the plane of the figure, the other, in the perpendicular direction. In this case it is said that deformation vibrations of the CO_2 molecule are doubly degenerate. The number of different states corresponding to one value of energy is called the degree (or multiplicity) of degeneration, or the *statistical weight* of the energy level, and is usually denoted by g .

When a state of the system under consideration changes, a quantum transition between energy levels occurs. Two kinds of transitions are distinguished for atoms and molecules: *collisional* transitions, occurring as a

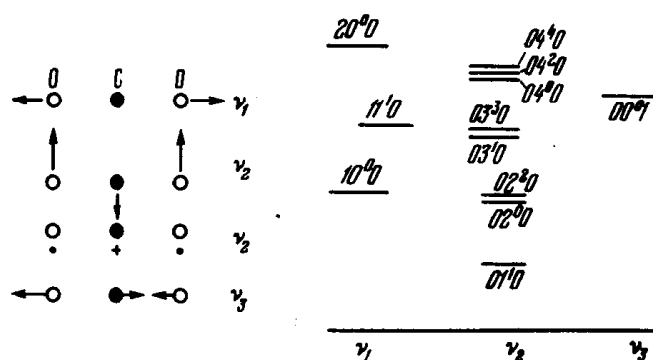


Fig.2.2.
Vibrational modes and
lower vibrational energy
levels for CO_2

result of collisions with other atoms and molecules, and *radiative* transitions, accompanied by radiation or absorption of light. For radiative transitions $E_m - E_n = h\nu$, where ν is the frequency of radiated or absorbed light. Here and below the subscript m designates the upper and n the lower energy level. To every transition there corresponds a line in the electromagnetic spectrum. The transition energy ΔE is related to frequency ν , wavelength λ , and wave number ν' as follows: $\Delta E = h\nu$, $\lambda\nu = c$, $\nu' = 1/\lambda$, where c is the speed of light.

In atoms only transitions between separate electronic energy levels are possible; a set of spectral lines corresponding to them is called the *line spectrum*. This spectrum is observed in visible and ultraviolet regions. In molecules transitions between rotational energy levels correspond to far infrared and millimeter spectral ranges, provided that other types of energy remain unchanged. In the infrared range vibration-rotational transitions are observed in which both kinds of energy change. Finally, in the visible and ultraviolet spectral ranges there occur transitions in which electronic, vibrational, and rotational energies change simultaneously. The corresponding spectra are of a band nature owing to the close location of the lines of the vibrational structure (vibrational lines). Such spectra are called the *band spectra*. The appearance of certain lines is determined by different selection rules (see, for example, [2.5-7]). It should be noted that in the infrared region the transitions with distortion of symmetry (dipole transitions) have an appreciable intensity. For instance, among diatomic molecules sufficiently intensive infrared spectra are observed for CO , NO , CN , etc. molecules, but not for O_2 , H_2 , and N_2 molecules.

Let us consider some examples which are interesting from the point of view of the subject matter of the book. The first concerns vibrational and rotational energy levels of the CO_2 molecule and its infrared spectrum.

In a ground electronic state CO_2 molecules are linear with axes of symmetry and symmetry planes perpendicular to them (see Fig.2.2). There are three typical modes of vibrations for CO_2 molecules: symmetric vibrations of oxygen atoms with respect to a carbon atom (the first mode ν_1), doubly degenerate symmetric deformation (bending) vibrations of oxygen atoms with respect to a carbon atom (the second mode ν_2), and antisymmetric valence vibrations (the third mode ν_3). To describe these vibrations three quantum numbers, ν_1 , ν_2 , ν_3 , respectively, are introduced. For doubly degenerate deformation vibrations one additional quantum number ℓ describes the quantization of the angular momentum associated with deformation vibrations and is directed along the axis of a molecule [2.7]. ℓ acquires the values $\ell = \nu_2, \nu_2 - 2, \dots, 0$ for even ν_2 , and $\ell = \nu_2, \nu_2 - 2, \dots, 1$ for odd ν_2 . The levels with $\ell = 0$ are nondegenerate, and those with $\ell > 0$ are doubly degenerate. Thus, the statistical weight of a level with a given ν_2 is $g_{\nu_2} = \nu_2 + 1$. The remarkable feature of the first two vibrational modes is that the fundamental frequency of the first mode (ν_1) and the double frequency of the second mode ($2\nu_2$) are almost equal (Fermi resonance). As a result of such a strong interaction, degeneracy is removed and splitting of the levels of the second vibrational mode is observed (see [2.7]). Vibrational energy levels of CO_2 are designated by the notation ν_1, ν_2^ℓ, ν_3 ; a schematic diagram of lower vibrational levels of this molecule is shown in Fig.2.2. To every level there corresponds a whole set of rotational levels which are not shown in the figure. Complete equations describing the positions of all vibrational levels of CO_2 taking account of interactions between vibrations and rotation can be found, for instance, in [2.7-9].

The Fermi resonance in the CO_2 molecule results in energy level shifts even for the lowest vibrational states. Under certain circumstances the resulting deviation from the harmonic oscillator model must be taken into account. In this case it is essential to realize that, owing to the Fermi resonance, the strict separation of symmetrical valence and symmetrical deformation modes of the CO_2 vibrations becomes impossible: these modes are mixed together. The levels of these mixed modes form a system which can be characterized by a quantum number $v = 2\nu_1 + \nu_2$, in the harmonic approximation each level of this system is doubly degenerate with a statistical weight $g_v = (v + 2)^2/4$ for even v , and $g_v = (v + 1)(v + 3)/4$ for odd v [2.10].

The selection rules for infrared transitions of CO_2 and other molecules are described, for example, in [2.7-9]. It should be noted that only those transitions, in which deformation or antisymmetric vibrations participate,

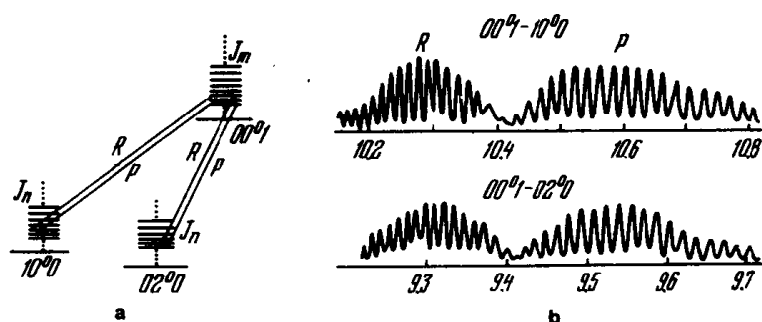


Fig.2.3a,b. R- and P-branch radiative transitions between rotational levels of the $00^0 1$, $10^0 0$, and $02^0 0$ vibrational states (a) and spectrum for these transitions (b) in CO_2

contribute to this spectrum. The rotational quantum number J either changes by ± 1 or does not change at all for certain bands ($\Delta J = 0$). Of great interest for us are the transitions $00^0 1 \rightleftharpoons 10^0 0$ and $00^0 1 \rightleftharpoons 02^0 0$, on which laser radiation of the highest power has been obtained in CO_2 (at a wavelength of 10.6 and 9.6 μm , respectively). A more detailed scheme of transitions between rotational lines for these bands is given in Fig.2.3a; here $\Delta J = -1$ (P branch) and $\Delta J = +1$ (R branch), other transitions being forbidden. A general view of a spectrum for these transitions is shown in Fig.2.3b.

In the infrared spectrum of CO molecules the most important for us is its anharmonicity, that is, a decrease of the vibrational quantum with an increase of the level number v according to (2.1.5). The most probable transitions here are between neighboring vibrational levels ($v \rightleftharpoons v - 1$), while higher harmonics $\Delta v \geq 2$ are less intense. The bands corresponding to these transitions are in a wavelength range of 4.7 μm .

Let us consider now one of the fundamental concepts of quantum electronics—*induced* and *spontaneous* transitions between energy levels. Suppose that an atom or a molecule is in an excited state m and has energy E_m . This excited state is unstable; in a certain time the atom will spontaneously pass over to a lower state n , emitting a quantum $h\nu$. This is a spontaneous transition. All spontaneous transitions obey statistical laws owing to the random nature of each act of spontaneous transition. The uncertainty of spontaneous transition results in the uncertainty of phase, direction of radiation, and polarization plane, since atoms emit independently and not at the same time. Hence spontaneous emission is incoherent and nonpolarized. Time dependence of a number of excited atoms N_m for spontaneous emission is expressed by an exponential law² (footnote see next page)