CO_2 Lasers

Effects and Applications

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Preface

It is now over 10 years since the CO_2 laser was developed. During that time the CO_2 laser has become well established as a tool in the laboratory, in the shop, and in the production line. The purpose of this book is to examine and to summarize some of the more important applications of this device in physics, chemistry, and engineering. Many of these applications use the CO_2 laser simply as a controllable and highly directional source of heat. Since this is a characteristic of all types of lasers, the discussion in this book often includes a consideration of the applications of lasers in general.

Several levels of treatment of the subject matter are presented. Many sections require little in the way of a mathematical background. In other sections a knowledge of university level mathematics or some specialized knowledge of another area of physics or chemistry is assumed. It is hoped that this treatment will make the book useful to the neophyte as well as the laser scientist and to undergraduates as well as graduate students. An introduction to lasers in general is given in Chapter 1; the discussion is kept at the elementary level.

CO_2 lasers as such are discussed fully in Chapter 2, while Chapter 3 is a fairly comprehensive overview of detectors, detection methods, windows, mirrors, and other optical components for use at 10.6 μm. As many industrial applications of the CO_2 laser derive from the use of this laser as a heat source, the relevant theory for laser–surface heating effects is presented in Chapter 4. This treatment is rigorous and is supplemented by tables and graphical data on thermal constants of many materials, so that the formulas derived may be readily applied to practical problems. A

summary of empirical observations on cutting, welding, drilling, and machining follows in Chapters 5 and 6.

Application of the CO_2 laser in the generation of other thermal effects is discussed in Chapter 9. Chapter 7 treats a number of applications of laser-induced evaporation including laser deposition of thin films, laser triggered switching, laser trimming of resistors, and applications in surface science.

Spectroscopy with lasers and laser photochemistry is surveyed in Chapter 8, which also includes a section on laser isotope separation.

The final chapter reviews applications of the CO_2 laser in meteorology and in communication systems.

An extensive bibliography covering the literature up to the end of 1974 is provided at the end of the book.

Acknowledgments

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I am indebted to Mrs. Doreen Myers for a superb job of typing the manuscript from handwritten copy and to Sally Lakdawala and G. R. Floyd for the preparation of the drawings.

I am most grateful to all those who freely granted permission to quote, adapt, or reproduce data from their publications.

Finally I offer special thanks to my wife and children for their encouragement and forbearance during the preparation of this work.

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Chapter 1

Introduction

1.1 HISTORICAL BACKGROUND

Infrared laser emission from CO_2 was first reported by Patel (1964) and others in pulsed discharges through pure CO_2. By the time more complete reports of this work had been published (Patel, 1964a,c) it had already been realized (Legay and Legay-Sommaire, 1964) that a much more efficient system based on the transfer of vibrational energy from N_2 to CO_2 was possible. A CO_2 laser based on this principle had soon been developed (Patel, 1964b) and is shown in Fig. 1.1. In this system N_2 is excited in a rf discharge to produce vibrationally excited N_2 ($X^1\Sigma_g^+ v'' = 1$) molecules, which stream into an interaction region to mix with unexcited CO_2. The CO_2 is then vibrationally excited through the reaction

$$N_2\,(X^1\Sigma_g^+\, v'' = 1) + CO_2\,(00^00) \rightarrow N_2\,(v'' = 0) + CO_2\,(00^01) - 18\ \text{cm}^{-1} \quad (1)$$

which occurs efficiently since thermal energies at or near room temperature are $\simeq$200 cm^{-1}. Laser emission subsequently occurs from rotational levels of the (00^01) state to rotational levels of lower vibrational states (see Fig. 2.22 for a complete description of the appropriate energy levels). Prior to the development of the CO_2 laser Polanyi (1961, 1963) had suggested that

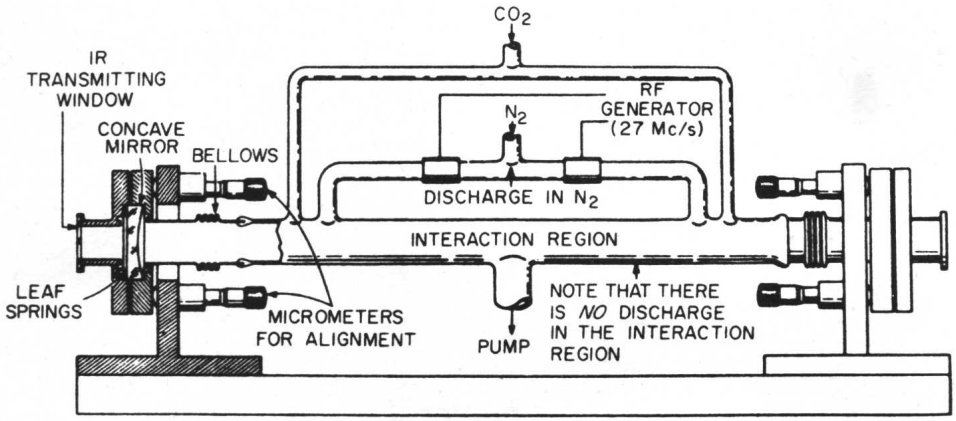

Fig. 1.1. System developed by Patel (1964b) demonstrating laser emission due to transfer of vibrational energy from N_2 to CO_2.

the type of resonant transfer of vibrational energy given in Eq. (1) might form the basis for a variety of efficient infrared lasers.

In these initial studies, continuously operating (cw) laser powers of 1 mW (Patel, 1964c) to 200 mW (Legay-Sommaire *et al.*, 1965) were obtained. The addition of N_2 was found to increase the overall efficiency from 10^{-6} (Patel, 1964c) to $\simeq 10^{-3}$ (Legay-Sommaire *et al.*, 1965; Patel, 1964b). Excitation of CO_2 in both these studies occurred as shown in Fig. 1.1. Direct excitation of a flowing mixture of N_2 and CO_2 or air and CO_2 using a dc discharge (Patel, 1965) was soon found to yield even higher cw output powers (11.91 W from a 2-m tube) and efficiencies that were $\simeq 3\%$. Cooling the gas to $-60°C$ improved the efficiency to $\simeq 5\%$ (Bridges and Patel, 1965).

Another major advance occurred soon after (Patel *et al.*, 1965), when the addition of helium was found to increase the cw power obtainable from a flowing N_2, CO_2 system to 106 W. The efficiency of this system was $>6\%$. Thus, in little over one year, the cw power obtained from the CO_2 laser had increased by a factor of 10^5 (from 1 mW to 10^2 W) and the efficiency with which this power could be generated had increased from 10^{-6} to 6×10^{-2}. Since the theoretical efficiency of the CO_2 laser operating at a wavelength of 10.6 μm is $\simeq 40\%$, while these early experiments showed that this figure could easily be approached in laboratory prototypes, the future of the CO_2 laser as an efficient converter of electrical power to infrared radiation was secure. By 1969 a 750-ft long cw CO_2 laser based on the design of Patel *et al.* (1965) had been built and operated at a power output of 8.8 kW (Horrigan *et al.*, 1969). Subsequently, the development of elec-

tric discharge convection and gas dynamic lasers (see Sections 2.3 and 2.4) has resulted in the generation of cw laser powers in excess of 100 kW.

The year 1969 marked a turning point in the development of high-power cw and pulsed CO_2 lasers. Late in 1969, Beaulieu (1970) reported that CO_2 laser emission could be obtained at atmospheric pressure and above by exciting the gas transversely so that the discharge passed perpendicular to the optical axis (Section 2.5). This has led directly to devices that rely on the creation of high densities of electronic charge using electron-beam excitation (Fenstermacher *et al.*, 1971) or volumetric photoionization (Seguin and Tulip, 1972) independent of the discharge that is used to excite laser emission. Using this approach, microsecond pulses with energies in the kilojoule range have been obtained. By way of contrast, pulse energies of 1.1 mJ were reported in the first study of a Q-switched CO_2 laser (Kovacs *et al.*, 1966).

The same year also saw the development of lasers based on convective cooling (Lavarini *et al.*, 1969; Deutsch *et al.*, 1969; Cool and Shirley, 1969) and a report was published describing the operation of a compact closed system cw laser using rapid transverse gas flow capable of generating output powers of 1 kW (Tiffany *et al.*, 1969).

The extraordinary increase in powers obtained from CO_2 lasers in the 10 years since Patel's first report has opened wide areas of application for these devices in basic and applied research and in many areas of technology. Now 10–15-kW cw CO_2 lasers can be purchased (Locke and Hella, 1974). While it is unlikely that a corresponding increase in power output will be obtained in the next 10 years, further advances can be expected.

1.2 INTERACTION OF LIGHT WITH A TWO-LEVEL SYSTEM

If we consider a system of N atoms or molecules each of which has only two electronic energy levels (Fig. 1.2), then when this system is exposed

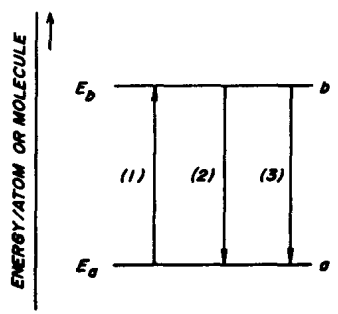

Fig. 1.2. Two-level system interacting with electromagnetic radiation of frequency ν_{ab}.

to light of frequency ν_{ab}, the electromagnetic field of the incident light will promote transitions between the two energy levels. The condition for this resonance is

$$h\nu_{ab} = E_b - E_a \tag{2}$$

where h is Planck's constant ($h = 6.626 \times 10^{-34}$ J-sec).

If this system is connected to a thermal reservoir at a temperature T (°K) and allowed to come to equilibrium, a well-known result of statistical mechanics predicts that the ratio of the number of atoms or molecules in level a to that in level b is given by

$$N_a/N_b = \exp[(E_b - E_a)/kT] \tag{3}$$

where k is Boltzmann's constant (1.38×10^{-23} J/°K). Since by definition $E_b > E_a$, N_a is always greater than N_b and at absolute zero all the atoms or molecules will be in the lowest energy level a.

Returning now to the effect of an incident radiation field at a frequency ν_{ab} we see that an atom or molecule in state a can be raised into state b by absorption of a photon of energy $h\nu_{ab}$. The rate at which this will occur is given by

$$R_1 = B_{ab}N_a\rho(\nu_{ab}) \tag{4}$$

where N_a is in m^{-3}, $\rho(\nu_{ab})$ is the energy density of the resonant frequency (J/m^3 Hz), and B_{ab} is the Einstein B coefficient, which is a measure of the strength of the $a \rightarrow b$ transition (in units of $m^3/J\text{-sec}^2$). R_1 is the rate at which atoms or molecules are transferred from level a to level b due to the incident field. However, this field can also induce the reverse transition, i.e., one in which an atom or molecule is caused to lose a quantum of energy to the radiation field while making the transition from level b to level a. The rate at which this occurs is

$$R_2 = B_{ba}N_b\rho(\nu_{ab}) \tag{5}$$

where N_b is the number of atoms or molecules in level b (per m^3). A simplification is obtained since $B_{ab} = B_{ba}$.

However, in the absence of an applied electromagnetic field, atoms or molecules in level b can spontaneously emit a quantum of energy $h\nu_{ab}$ to drop to level a. The rate at which this occurs is

$$R_3 = N_bA_{ba} \tag{6}$$

where A_{ba} (sec^{-1}) is the Einstein A coefficient and is simply the inverse of the radiative lifetime τ_{ab} of the upper level. Also

$$A_{ba} = (8\pi h\nu_{ab}^3/c^3)B_{ba} \tag{7}$$

where c is the velocity of light. Since we have only two energy levels and the atoms or molecules in the system must be in either one of the two levels we can write

$$R_1 = R_2 + R_3$$

or

$$N_a\rho(\nu_{ab})B_{ab} = N_bA_{ba} + N_b\rho(\nu_{ab})B_{ba} \tag{8}$$

Two immediate conclusions that can be obtained from this simple analysis are that, first, as $N_a > N_b$ the system will always absorb energy from the incident radiation field at a greater rate than energy is returned to the field through stimulated emission, and second, that even when $\rho(\nu_{ab})$ is made very large, the effect on the system will be only to equalize the populations in the two energy levels ($N_a = N_b$). The first effect accounts for the fact that systems at a lower temperature than the temperature of a background light source always appear to absorb incident radiation, while the second effect is responsible for the saturation that occurs in absorbing systems at very high incident light levels. A system in thermal equilibrium or any system in which $N_a > N_b$ can only act as an attenuator for incident radiation of frequency ν_{ab}. Even when $N_a = N_b$ [infinite temperature or infinite $\rho(\nu_{ab})$] the system only provides a rate of stimulated emission that exactly balances the rate at which incident radiation is removed through absorption. To obtain a system in which the stimulated emission term is larger than R_1 we must have $N_b > N_a$ or a population inversion between the two levels. To make full use of this population inversion we want to make $\rho(\nu_{ab})$ as large as possible so that R_2 can be kept large. This latter requirement is necessary only if it is desired to turn the system from an amplifier at frequency ν_{ab} to an oscillator.

Practical laser systems are always more complex than this: one never has simply two energy levels involved. However, the net result is always to produce a population inversion between pairs of energy levels so that the stimulated emission term can become dominant.

1.3 THE PRODUCTION OF POPULATION INVERSION

We have seen that in a two-level system a means by which N_b can be made greater than N_a must be found in order that the system may act as an amplifier for radiation of frequency $\nu_{ab} = (E_b - E_a)/h$. Two ways in which this can be accomplished are shown schematically in Fig. 1.3. Figure 1.3a is a representation of the energy level diagram in a typical solid state laser system in which pumping is done optically while Fig. 1.3b is a simplified schematic of the energy levels in the CO_2 laser pumped by resonant energy transfer from electrically excited N_2.

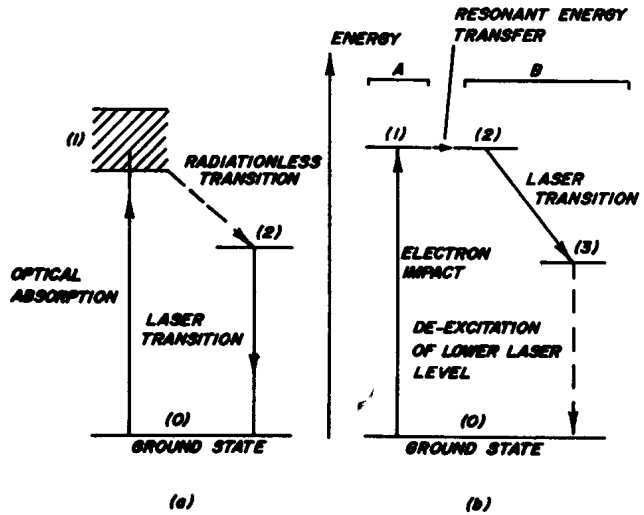

Fig. 1.3. Pumping mechanisms in two representative laser systems. (a) Solid state laser, e.g., ruby. (b) Gaseous laser, e.g., CO_2, N_2, or He. A could be N_2, while B would be CO_2.

In the optically pumped system, a strongly allowed transition connects the ground state (0) of the laser ion (Cr^{3+} in ruby) to a broad electronic energy level (1) that lies at an energy above that of the upper laser level (2). Since this energy level is broad a large amount of the radiation from the pump can be absorbed, making for efficient operation. Electrons transferred to energies within this band rapidly settle to the bottom of the band where they can lose their energy either by making the radiative transition (1) $\rightarrow$ (0) or by undergoing a radiationless transition to level (2). In ruby, the radiative transition (1) $\rightarrow$ (0) occurs with less probability than the radiationless (1) $\rightarrow$ (2) transition. Thus, most of the electrons transferred into level (1) by the absorption of pump radiation rapidly relax into level (2). If level (2) is metastable, that is if it has a long radiative lifetime $\tau_{20} = A_{20}^{-1}$, then this population can build up until stimulated emission becomes important. When the pumping is continued, a population inversion may be created between levels (2) and (0). Note that as the number of ions in the system is finite, the ground state population is reduced by optical pumping, which aids the attainment of inversion between levels (2) and (0).

The system shown in Fig. 1.3b is representative of the situation in a CO_2 laser discharge. The discharge excites N_2 molecules electrically to establish a population in energy level (1). Practically, the only way in which this energy may be dissipated is by means of resonant energy transfer to a