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W. J. Witteman

The CO_2 Laser

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The CO_2 Laser

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To *Ellen*
Willem
Agnes
Marc
Gemma

Preface

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The field of CO_2 lasers has grown enormously in the last two decades. It has not only provided us with much insight into the features typical of molecular lasers and demonstrated different device concepts, but has also found a wide range of applications. This monograph is primarily devoted to those developments of the CO_2 laser that have become well established. It gives an extensive treatment of the relevant molecular physics, gas kinetics, excitation and relaxation processes, and laser physics pertinent to carbon dioxide. Furthermore, it provides a thorough theoretical background to specific technologies used in various devices. Many numerical values of physical constants and accurate spectroscopic data for CO_2 isotopes are also included. In fact, the book is based on the history of the CO_2 laser starting in 1964 and it reflects the subsequent developments in which I was actively engaged from the beginning.

Most of the new device concepts were initiated as the result of pure scientific research in many laboratories all over the world, irrespective of applications. On the other hand, many important potential applications have had a very stimulating effect on the further development of dedicated devices. This is particularly true for the spectacular progress made in high-energy pulsed systems in the range of 100 kJ to be used in experiments connected with laser fusion. Although the physics of short-pulse amplification and the technical problems related to these so-called e-beam sustained CO_2 laser systems are treated, a full description of the huge systems for laser fusion is beyond the scope of this book.

There are several books on laser physics, but none is devoted exclusively to CO_2-laser physics and devices, nor are their treatments of this subject very detailed. The aim of the present monograph is to bridge this gap. It will contribute to the understanding of different laser performances and will provide insight into the great potential of the CO_2 laser. The theories presented here are developed to show their relevance both to basic physics and to technology, and in most cases experimental results are compared with theory. Topics that are more general in laser physics, such as the optical properties of resonators, which can easily be found elsewhere, are not described extensively but only as far as is relevant to a particular system's performance. This book should be a useful handbook for experimental physicists and engineers in the field of CO_2 lasers. The work will also be useful to the graduate student or applied scientist with a scant background in laser physics.

I wish to thank many of my co-workers who have contributed with their own research to much of the material presented in this book. I would especially like to mention Dr. R.J.M. Bonnie, Dr. G.J. Ernst, Dr. F.A. van Goor, Dr. A.H.M. Olbertz, and Dr. R.A. Rooth. I am also indebted to Simone Sloot for the accurate typing of the manuscript and to H.T.M. Prins for the illustrations.

Enschede, December 1986 *W.J. Witteman*

Contents

1. Introduction

The development of various types of CO_2 lasers has been spectacular. The first reported laser had a continuous output power of only a few milliwatts [1.1, 2]. Nowadays continuous lasers are built with output powers of more than 20 kW [1.3]. For pulsed systems it started in 1968 with a few joules [1.4]. These developments, especially stimulated by the large laser-fusion projects, have led to huge systems in the range of 100 kJ. Not only the pulse energy but also its time profile has been intensively studied. The search for pulse-compression technology has resulted to pulse durations of less than one picosecond [1.5].

When the potentialities of the CO_2 laser were recognized many industrial laboratories, institutes, and university groups were highly interested in this type of laser research. Not only new versions with very different output formats appeared during the course of time, but most of the research was devoted to the optimization of the performance, i.e. studies on extractable power, stability, beam divergence, mode structure, pulse shape, spectral purity, etc. The limits of the output power and pulse energy are, apart from costs, probably only restricted by the damage threshold values of transmitting and reflecting optical components.

The large interest in CO_2 lasers can also be understood from the fact that the efficiency of conversion of electrical energy into laser radiation combined with the maximum available power or pulse energy is by far superior to that of other laser systems.

The creation of the various categories of CO_2 lasers and the continuous improvements of them during the last decades were made possible by the broad interest of physicists and engineers with different backgrounds. In particular, the breakthrough in pulsed systems was possible because of many fundamental studies on glow discharges of molecular systems at atmospheric pressure and the introduction of new techniques for preionization.

With respect to applications, the CO_2 lasers have generally proven to be very versatile, simple to operate, and relatively cheap on investment and maintenance.

1.1 Applications

A large-scale application of the CO_2 laser is its use for material processing. In many cases the laser turns out to be superior to conventional tools. The advantages are the excellent control of the beam power, the absence of mechanical contact with the work piece, and the sharp focusing of the laser beam in the region of interest so that the applied energy is restricted and undesired deformation or decomposition of material can be avoided.

The technology of cutting and welding of metals with CO_2 lasers has been very successful. Steel plates of several centimeters thickness can be easily cut with a 10 kW system; and thin foils with low-power systems. Various metals that cannot be welded by conventional techniques can now be treated with CO_2 lasers.

Low-power lasers below 100 W have found their way onto the production floor where they perform a variety of micromachining and microsoldering tasks. Ablation, melting of thin metal layers, and vaporization without thermal side effects are possible. The 10 μm wavelength of the CO_2 laser is better absorbed and hence more efficient than the near-infrared radiation of solid-state lasers for processing many synthetic materials. For that reason the CO_2 is also very efficient for marking.

Very short pulses with high energy are of great interest for laser fusion. When a small pellet with a diameter of a few tenths of a millimeter filled with a mixture of deuterium and tritium, is irradiated with a high-energy laser pulse of the order of 100 kJ it is observed that the expanding plasma created by the strong absorption compresses and heats the center part of the pellet at values that initiate fusion. Although it is not our intention to describe the huge systems that have been developed for this technology, the large programs on laser fusion had a tremendous impact on the technology of amplifying and generating short pulses.

Low-power systems have also proven to be successful in many specialized surgical applications. Using a micromanipulator and an endoscopic coupler, the accuracy, reduced bleeding, and reduced post operative pain have made the CO_2 laser a valuable addition to the otolaryngology logic armamentarium. Neurosurgery too is using these lasers with great benefits to patients.

Finally we mention that military systems are often equipped with lasers. CO_2 lasers are used for tactical systems like target sensing, precision guidance, and coded communication.

1.2 Efficiency and Output Considerations

The CO_2 laser like any other gas laser consumes electrical power and delivers less power in its radiation at about 10 μm wavelength. The difference between input and output power is waste heat that must be consumed. To increase the output power one must increase the input power, but technical and physical constraints limit the amount of input energy. In fact, the choice of heat sink characterizes the type of laser, examples being continuous sealed-off systems, fast-flow high-power systems, and pulsed systems.

The CO_2 laser operates by exchanging energy between low-lying vibrational-rotational energy levels of the CO_2 molecule. Molecules being in the higher energy state are transferred by the radiation field into a vibrational energy mode with a lower-energy state. The difference of energy of these upper and lower states is converted into infrared radiation. The upper level is excited by an electrical discharge either from the ground state or from a resonance transfer by vibrationally excited nitrogen. In both cases the input energy is at least the energy of the upper state. The maximum efficiency that is achievable is then 38 %, as can be directly inferred from an energy level diagram. However, this efficiency is the theoretical limit and no actual CO_2 laser will ever achieve this quantum efficiency. Well-designed systems reach at most 20 % of the electrical input energy.

The lasing process of all CO_2 lasers is sensitive to the temperature of the gas molecules in the discharge, i.e. active medium, which imposes another limit. As more power goes into the gas, its temperature rises and with this the thermal population of the lower laser level. Consequently, more radiation will be lost by the absorption of the lower-level density. In practice, therefore, one observes for increasing input energy, at first an increasing output but at a certain stage the output levels off and begins to decrease when the gas temperature rises above about 150°C.

Knowing these principal limitations one may estimate the output capability of a system. It depends entirely on the method by which the attendant waste heat is removed from the system. There are three basic routes to dispose of this waste energy. The simplest one is to make use of the thermal conductivity of the gas. The waste heat will be conducted to the cooled walls of the vessel containing the discharge. This method is always found in continuous systems with output powers in the order of 100 W or less. A second method to get rid of the waste heat is the removal of the hot gas itself. This is the case for the so-called fast-flow systems which operate in the range of many kilowatts of output power. The third method takes advantage of the heat capacity of the active medium. The maximum input energy, again limited by the gas temperature, is roughly 300 J per liter laser gas at atmospheric pressure. The output power is then about 40 J per liter active medium at one atmosphere. Both input and output energies are proportional to the gas density.

1.3 Stable or Unstable Resonators

The structure of the optical resonator of the laser system determines, to a large extent, the radiation distribution within the active medium and the optical quality of the outcoming beam. For obtaining nearly complete energy extraction from the laser medium the beam must not only fill the entire medium but its intensity must be above the saturation value in order to convert the inverted population into radiation. The design of the resonator, therefore, has a large influence on the laser performance.

The resonator can be either stable or unstable. For a stable resonator the mirror configuration corresponds to a stable periodic focusing system [1.6,7]. The outcoming beam is transmitted through one or both mirrors. The mirror surfaces intersect the beam along phase fronts so that the reflected waves coincide with the incident wave. The stability relations can be obtained from the laws of geometrical optics and are given by

$$0 \leq (1 - L/R_1)(1 - L/R_2) \leq 1 \,, \tag{1.1}$$

where L is the distance between the mirrors, and R_1 and R_2 are the radii of curvature of the mirrors (a concave mirror has a positive R value and a convex mirror has a negative R value).

For an unstable resonator the radiation is not confined to narrow beams but experiences defocusing by bouncing back and forth between the mirrors. The divergent resonator system expands the radiation field on repeated bounces to fill the entire cross section of at least one mirror. The radiation leaving the cavity propagates around rather than passing through the outcoupling mirror. Unstable configurations are found when conditions (1.1) are not fulfilled. Typical examples of a stable and an unstable resonator are shown in Fig. 1.1.

Physical optics teaches that the oscillating beam in a stable or unstable cavity consists of one or more modes, each having its own spatial distribution. For a not too small Fresnel number (defined below) the stable

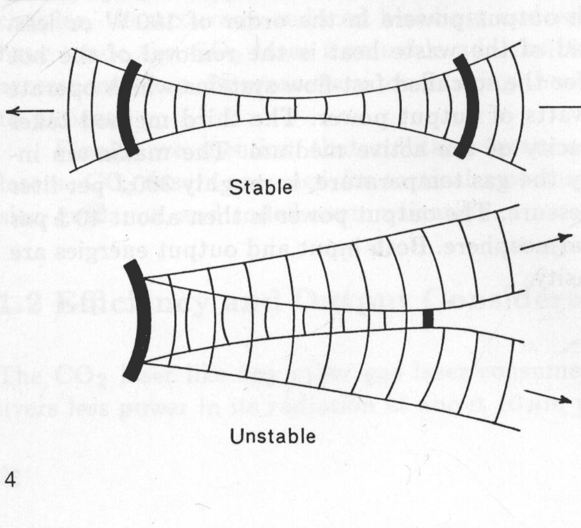

Fig. 1.1. Examples of stable and unstable resonators

resonator produces, for the lowest-order mode near the axis, a Gaussian field distribution perpendicular to the optical axis [1.8]. The diameter of this lowest order or Gaussian mode is roughly given by a few times $(L\lambda)^{1/2}$, λ being the wavelength. It is generally less than the diameters of the mirrors. The Fresnel number, defined as $N_\mathrm{F} = a^2/L\lambda$ with $2a$ being the diameter of the cavity or laser medium, indicates the number of different modes that are more or less free to oscillate. For a Fresnel number much larger than unity the Gaussian modes fill about a fraction $1/N_\mathrm{F}$ of the laser medium. The whole medium can then only be filled with higher-order transversal modes. A great number of modes are needed to extract the available energy. The beam quality or beam divergence of the multi-mode system is inferior compared to a single-mode beam. Since each mode is characterized by a frequency, the frequency band of the multi-mode output beam can be a considerable fraction of the line width of the laser transition.

For the unstable resonator the situation is very different. Theoretical [1.9] and experimental studies [1.10] have clearly shown that unstable resonators can have large mode volumes even in short resonators and that the lowest-order mode may fill the total volume enclosed between the mirror geometry. This mode having the lowest loss per bounce will suppress the oscillation of other modes so that this type of resonator has a large discrimination against higher-order modes. The active medium is then occupied by a single-mode radiation field.

A theoretical analysis for numerical computations of the diffraction losses, i.e. outcoupling, and the field distribution is based on the Huygens integral equation [1.7,11]. This method is complicated and laborious. A much easier approach is reached by a geometrical description that relies on the focusing or defocusing effects of the mirrors. It produces an outcoupling factor which turns out to be in good agreement with the more detailed physical analysis based on Huygens' integral. In fact, it provides a more or less accurate zero-order approximation for the lowest-order mode, but not for any of the higher-order modes [1.12–14].

We shall describe the geometrical approach of the unstable resonator [1.12]. In Fig. 1.2 the two mirrors with radii of curvature of respectively R_1 and R_2 are shown. The separation distance is L. Both mirrors reflect the

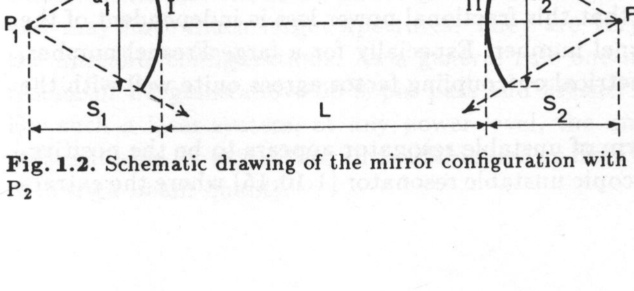

Fig. 1.2. Schematic drawing of the mirror configuration with the virtual images P_1 and P_2