Gasdynamic Lasers: An Introduction

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Preface

Lasers (light amplification by stimulated emission of radiation) have been part of modern science and technology for only a short fifteen years; yet during that time they have experienced a rate of growth and achieved a maturity that have been almost phenomenal in the history of physical science. In addition, the applications of the monochromatic, highly columnated visible or infrared beams of radiation produced by these lasers have also multiplied at an equally phenomenal rate. It is safe to say that the laser has become a permanent fixture in most modern physics, chemistry, and engineering laboratories. Moreover, even the layman is generally acquainted with the typical "garden variety" of low power lasers (such as the ruby or He–Ne lasers) from science classes, technology museums, demonstrations, or direct professional use.

This book does not deal with typical "garden variety" lasers. Instead, it focuses on the gasdynamic laser—a revolutionary device which, in 1966, created a breakthrough in high energy laser technology. With the gasdynamic laser, the dream of producing laser beams transmitting tens or hundreds of kilowatts for durations of seconds, or even minutes, suddenly became a reality. To date, the gasdynamic laser has seen at least two major development generations, and its technology has matured to the state at which it can logically be presented in a text, studied, and analyzed. This is precisely the purpose of this book.

It is written for at least three groups of people: (1) students who are interested in studying an example of interdisciplinary applied science in action, (2) professional scientists and engineers who, without previous experience in this area, want to learn how and why gasdynamic lasers work, and (3) workers in the field who want a convenient review and reference source reflecting the fruits of their labor. In addition, gasdynamic laser technology overlaps the various fields of aerodynamics, physical chemistry, quantum mechanics, spectroscopy, and physical optics. The reader is *not* expected to be an expert in any or all of these fields. For this reason, the fundamental elements of each field are developed as needed for application to gasdynamic lasers. The intent is to provide a book from which readers with various backgrounds can obtain a coherent education in gasdynamic lasers.

The style of the book is intentionally informal. The author sees no reason for a technical or scientific text to be rigid or sterile in its presentation; instead, the present book attempts to "talk" to the reader, hopefully guiding him along the paths from fundamental principles to specific applications with a minimum of confusion and a maximum of interest. The science and technology associated with gasdynamic lasers is exciting and challenging. The intent here is to convey this excitement and to give the reader the extent of pleasure that should go hand-in-hand with the acquisition of new knowledge.

Acknowledgments

Through the kindness of Dr. Kurt Enkenhus of the Naval Ordnance Laboratory and Dr. John Wendt of the von Karman Institute, the author was invited to give the lectures on gasdynamic lasers during a course on "High Power Gas Lasers" presented at the von Karman Institute for Fluid Dynamics, Brussels, Belgium, in March 1974. During and after this course, numerous students approached the author, suggesting that the lectures be amplified into a book on gasdynamic lasers. Their encouragement was so compelling and emphatic that it could not be ignored. This book, considerably extended and amplified in depth and scope over the original lectures, is the result.

Some other acknowledgments are due. First, the state-of-the-art of gasdynamic lasers exemplified by this book was developed through the toil, efforts, insight, and intelligence of numerous teams of engineers and scientists in laboratories throughout industry, government, and universities. It is impractical to list them all here, but their work is detailed throughout this book. The author wishes to give special acknowledgment to his colleagues of seven years at the Naval Ordnance Laboratory, especially John Vamos and Mike Plummer, who obtained considerable gasdynamic laser data from experiments with a shock tube; Richard Humphrey and Eva Winkler, who converted an arc tunnel to a gasdynamic laser; Walter Glowacki, Michael Madden, and Jerry Wagner, who performed various analyses; and E. Leroy Harris, who guided all of us in the right direction. The author is proud to be listed among these ranks.

There is one other ingredient in all books of this nature, and that is the huge amount of time necessary to prepare the material in a fashion that can be digested by the reader. The author gives special thanks to his wife, Sarah-Allen, and his daughters, Katherine and Elizabeth, who relinquished hours upon hours of valuable family time with their husband and father so that he could accomplish this task. Also appreciated are the many hours of work spent by Mrs. Edna Brothers in typing the manuscript. To all of these friends and loved-ones, the author says thank you, and breathes a sigh of relief.

Contents

Chapter I

Introduction

High energy gas lasers are a modern reality. It is now feasible to produce near-diffraction-limited laser beams with cross-sectional areas the size of the cover of this book, transmitting hundreds of kilowatts for durations of seconds or minutes depending on the practical design and capacity of the gas supply and hardware components of the device. This statement could not have been made ten years ago. What has spearheaded this breakthrough in high energy laser devices in the past decade? The answer—gasdynamic lasers—is the subject of this book.

In 1965, the only high energy gas lasers operating on a practical basis were conventional electric discharge lasers [see Patel (1968) for a particularly lucid description of the CO_2 electric discharge laser]. In such devices the laser gas is produced by an electric discharge that not only ionizes the gas to sustain the discharge itself, but that also preferentially excites various vibrational or electronic energy levels of the molecules or atoms. Such preferential excitation can result in a population inversion; hence laser action occurs. It is commonplace to obtain watts, and even a few kilowatts, of continuous wave power from such lasers. However, conventional electric discharge lasers are not easily scaled to arbitrarily large sizes and powers because the physics of electric discharges favors undesirable arcing in large scale devices, and the heating of the laser gas by the discharge can reduce or even destroy the population inversion, hence terminating the laser action. This latter objection can be partly overcome by flowing the gas at high speeds (subsonic or even supersonic) through the laser cavity. Nevertheless, in 1965, hopes for a truly high power gas laser were languishing; the best that could be obtained was about 9 kW from laser tubes about 200 ft long!

However, the seeds for a revolution in high power gas lasers were planted in 1962 by Basov and Oraevskii (1963), who suggested that population inversions in molecular systems could be created by rapid heating or cooling of the system. Subsequently, Hurle and Hertzberg (1965) suggested that such cooling and population inversions could be obtained in the rapid, nonequilibrium expansion of an initially hot gas through a supersonic nozzle. They considered the specific case of electronic level inversions in expanding Xe but were unsuccessful in measuring such inversions in the laboratory. Then, Kantrowitz (1946) combined this idea with his previous work on vibrational nonequilibrium in CO_2, and, in 1966, he and a group of physicists and engineers at the Avco Everett Research Laboratory operated the first gasdynamic laser, using a mixture of CO_2–N_2–H_2O (see Gerry, 1970).

These events were truly revolutionary. To fully appreciate this, first consider in your imagination a supersonic wind tunnel such as those commonly found in many aerodynamic laboratories. However, when this particular tunnel is turned on, we do *not* measure the lift and drag on an aerodynamic model or the pressure and heat transfer distributions over a surface. Instead, when the switch is thrown for this particular tunnel, we see *a very powerful laser beam propagating from the test section.* Indeed, this is not a wind tunnel at all, but rather it is a *gasdynamic laser.*

As shown schematically in Fig. 1.1, a gasdynamic laser takes a hot, high pressure mixture of gases (usually CO_2, N_2, and H_2O or He) and expands this mixture very rapidly through a supersonic nozzle. During the expansion, the gas is turned into a laser medium (i.e., a population inversion is created). The supersonic laser gas then passes into the test

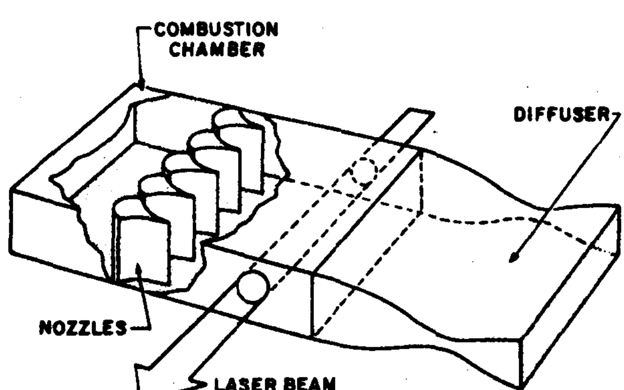

FIG. 1.1 Schematic drawing of a conventional gasdynamic laser. (After Monsler and Greenberg, 1971.)

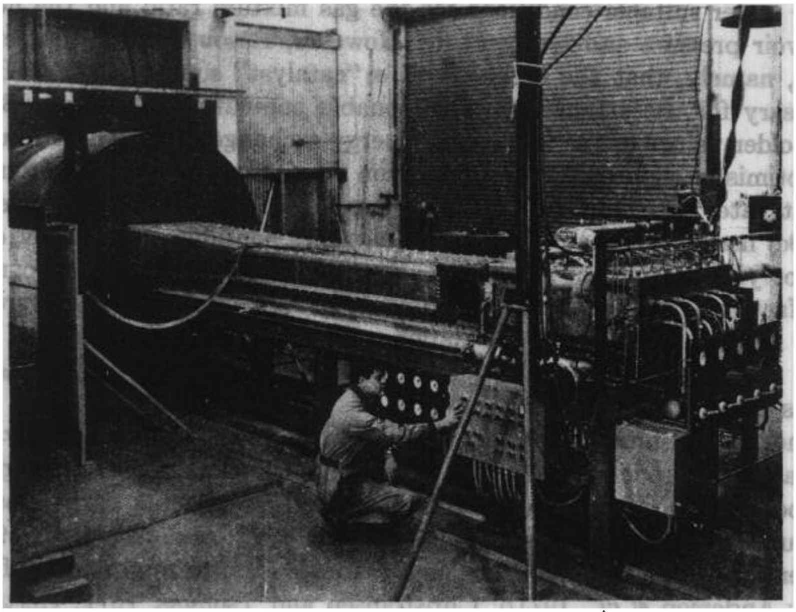

FIG. 1.2 135 kW gasdynamic laser at Avco Everett Research Laboratory, Inc. (After Gerry, 1970.)

section (laser cavity) where, if mirrors are placed on both sides of the test section, a beam of laser energy is extracted perpendicular to the flow. The supersonic stream then enters a diffuser where it is shocked down to subsonic speeds and generally exhausted to the atmosphere.

The revolutionary aspect of a gasdynamic laser is that, unlike the early electric discharge lasers with their attendant problems of arc discharges in large volumes, gasdynamic lasers can be scaled to large sizes without major physical complications. This is because the population inversions are produced by purely thermal means within the supersonic expansion, and such gasdynamic processes are not dependent on the lateral extent of the supersonic flow. For example, a multimode, continuous wave power output of 60 kW from a CO_2–N_2–H_2O gasdynamic laser has been reported by Gerry (1970), and an average laser power of 400 kW has been extracted for 4 msec from a shock tube gasdynamic laser by Klosterman and Hoffman (1973) working in the laser group at the University of Washington. A picture of a large-scale gasdynamic laser is shown in Fig. 1.2.

As part of the early development of the gasdynamic laser, Basov *et al.* (1968) carried out a theoretical analysis of population inversions in CO_2–N_2 expanding mixtures and predicted that substantial inversions can indeed occur under suitable conditions for the gas mixture ratio and the nozzle reservoir pressure and temperature. However, Basov missed an essential point, namely, that the inclusion of a "catalyst" such as H_2O or He is necessary for the attainment of reasonable population inversions. Basov used older values of the vibrational energy exchange rates, which resulted in optimistic values of the population inversions; indeed, using more recent rates as compiled by Taylor and Bitterman (1969), Anderson (1970c) has shown that the CO_2–N_2 mixtures considered by Basov *et al.* do not yield significant inversions. The group at Avco first recognized this fact and have reported experiments using CO_2–N_2–H_2O mixtures as early as 1966. Theoretical calculations showing the beneficial role of H_2O were reported by Anderson (1970c) in 1969. The exact role of H_2O or He as a catalyst is discussed later in this book.

Since these initial experiments and calculations, the technology and fundamental understanding of CO_2–N_2 gasdynamic lasers has grown precociously. This growth is exemplified by experiments carried out in arc tunnels (Lee and Gowen, 1971; Lee *et al.*, 1972; Anderson *et al.*, 1971b; Anderson and Winkler, 1971), shock tunnels (Klosterman and Hoffman, 1973; Anderson *et al.*, 1971b; Christiansen and Tsongas, 1971; Hertzberg *et al.*, 1972; Vamos, 1974; Tennant *et al.*, 1974; Kuehn and Monson, 1970), and combustion driven devices (Gerry, 1970; Tulip and Sequin, 1971; Yatsiv *et al.*, 1971; Meinzer, 1972), and by theoretical calculations reported by Basov *et al.* (1968), Anderson (1970c), Anderson *et al.* (1971b), Anderson and Winkler (1971), Anderson and Harris (1972a,b), Anderson (1972a,b, 1973, 1974), Hoffman and Vlases (1972), and Murty (1974). Moreover, gasdynamic lasers using CO as the lasing medium have also been demonstrated (McKenzie, 1972). It is the purpose of this book to bring the reader up-to-date in this exciting state-of-the-art, while at the same time developing the underlying physical and gasdynamic fundamentals that govern such devices.

Chapter II

Elementary Physics

Gasdynamic lasers are truly interdisciplinary devices. The concepts and design of gasdynamic lasers cut across such disciplines as quantum mechanics, statistical thermodynamics, physical chemistry, nonequilibrium gasdynamics, physical optics, and the aerodynamics of internal flows. It is unrealistic to assume that any single person is a master of all these fields; hence, wherever appropriate throughout this book, the fundamental physical principles underlying various aspects of gasdynamic lasers will be discussed in a somewhat self-contained manner. In particular, Chapters II, III, and IV discuss the basic detailed physical phenomena that ultimately are responsible for producing gasdynamic laser action. Comprehensive treatments of the background laser physics can be found in such books as Siegman (1971) and Lengyel (1971), and the fundamentals of nonequilibrium gasdynamics are thoroughly treated in Vincenti and Kruger (1965) and in Clarke and McChesney (1964). The necessary elements of quantum mechanics and statistical thermodynamics are nicely developed by Davidson (1962).

2.1 Energy Levels and Population Inversion

Consider a collection of molecules in a gas. Pick one of the molecules and examine it. The molecule is moving about in space—it has translational energy; it is rotating about its principal axes—hence it has rotational kinetic energy; the atoms that make up the molecule may be vibrating back and forth from some equilibrium position—it has vibrational kinetic and potential energy; and, finally, the electrons move about the nuclei of the molecule—hence it has kinetic and potential energy of electronic origin. However, the amazing quality of these various forms of molecular energy is that they *cannot* be any arbitrary value. Rather, one of the most important discoveries of modern physics is that the molecule, at any given instant, *has to occupy one of a very specific set of energy levels*; i.e., the energy values of a molecule are *quantized*. This is shown schematically in Fig. 2.1. Instead of one molecule, imagine the whole collection, say 10^6 molecules, and look at the first quantized energy level ϵ_0 (the ground state). There may be 400,000 molecules in this level at some instant in time. The number 400,000 is called the population N_0 of the ϵ_0 level. Next, look at the first excited level, ϵ_1; there may be 200,000 molecules in this level, hence $N_1 =$ 200,000 = the *population* of the ϵ_1 level, and so forth. The *set* of numbers, $N_0, N_1, N_2, \ldots, N_i, \ldots$ is called the *population distribution* over the energy levels of the gas. The *nature* of this population distribution is of vital importance for laser action. For example, consider the *vibrational energy* of a molecular gas. If the gas is in thermodynamic equilibrium, the population distribution will exponentially decrease with increasing ϵ_i, as shown in Fig. 2.2a; i.e., it will follow a Boltzmann distribution. A major characteristic of this equilibrium distribution is that $N_{i+1} < N_i$. However, if the gas is disturbed at any instant, say by means of an electric discharge or by a very sudden temperature change, then the population distribution can become a nonequilibrium distribution, and it is even possible that, at some instant, $N_{i+1} > N_i$. This situation, in which the number of molecules in a *higher* lying energy level is *greater* than the number in a *lower* lying level, is called a *population inversion*. The population inversion is the

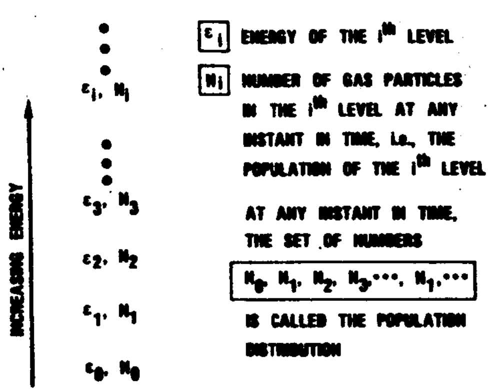

FIG. 2.1 Energy levels, populations, and population distributions.