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Mansoor Sheik-Bahae

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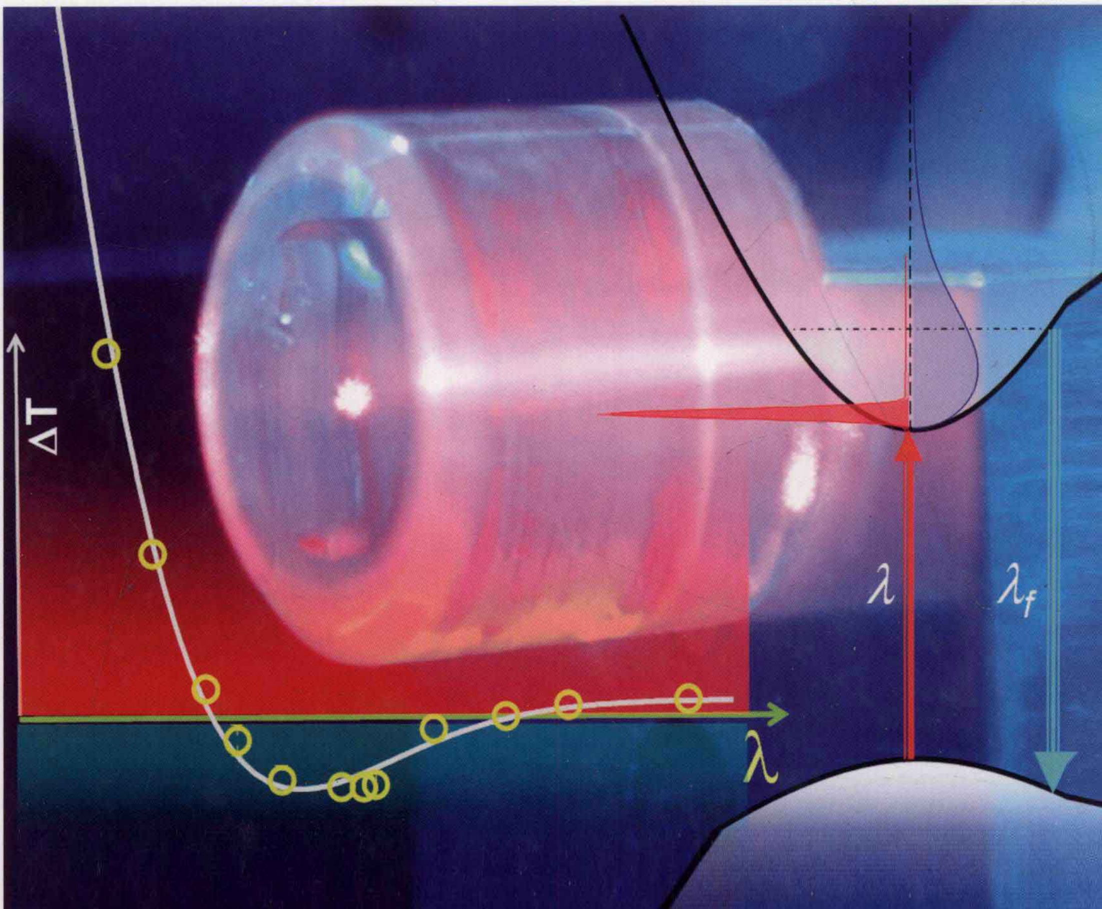
Optical Refrigeration

Science and Applications of Laser Cooling of Solids



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Preface

Laser cooling of solids or "optical refrigeration" is a research area that encompasses basic scientific questions regarding the interaction of light with condensed matter systems and the practical issue of the design and construction of practical laser-powered cryocoolers. This volume brings together leading researchers to describe the critical issues being investigated and the approaches they are pursuing. There are two general thrusts to the current research programs: laser cooling of solids containing rare-earth (RE) ions, and the cooling of direct bandgap semiconductors. The advantages of using rare-earth-doped solids for laser cooling had been known for decades. The key optical transitions in RE-doped ions involve 4f electrons that are shielded by the filled 5s and 6s outer shells, which thus limit interactions with the surrounding lattice. Nonradiative decays due to multiphonon emission are thus suppressed.

Laser cooling of a solid was first experimentally demonstrated in 1995 with ytterbium-doped fluoride glass. Since then, researchers have demonstrated laser-induced cooling in a broad range of glasses and crystals doped with ytterbium. Later, laser cooling was achieved in thulium-doped fluoride glass. More recently, erbium-doped glasses and crystals have been laser cooled. Laser cooling of semiconductors has been more problematic. Direct bandgap semiconductors have several potential advantages over rare-earth-based cooling materials. These materials interact with light more strongly and have the potential to cool at much lower temperatures with higher cooling power densities. Additionally, they can be directly integrated into electronic and photonic devices. However, these materials have their own challenges. Semiconductors typically have high refractive indices that enhance total internal reflection and lead to luminescence trapping. Because of modest quantum efficiencies and heating from reabsorbed luminescence, net cooling is yet to be observed in semiconductors.

Chapter 1 provides an overview of research issues in optical refrigeration. It summarizes the physics of laser cooling in rare-earth-doped solids and in semiconductors and examines current research challenges. The factors that limit cooling performance in rare-earth-based coolers are parasitic heating from impurities and from components of the coolers such as the mirrors that form the cavity used to trap the pump radiation. The authors describe ongoing efforts to mitigate these problems. This chapter examines approaches to laser cooling in semiconductors

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that attempt to overcome nonradiative recombination electron–hole excitations and luminescence trapping. In particular, it addresses the interplay of properties such as quantum efficiency, excitation density and extraction efficiency, which must be adjusted to achieve effective cooling.

In Chapter 2, Markus Hehlen describes the program at Los Alamos National Laboratory to develop ultrapure rare-earth-doped glasses that will be more efficient in laser cooling. He first summarizes the current status of the laser cooling of rare-earth-based laser cooling materials and then explains the advantages and constraints that must be considered when selecting rare-earth dopants and host materials. Dr. Hehlen discusses the harmful effects of impurities, such as OH ions and transition metals. He then describes the program in his laboratory to produce chemicals that have extremely low levels of impurities and to produce nearly defect-free glass samples for laser cooling. He ends with a discussion of halide crystal growth and some promising materials for laser cooling that may be developed in the future.

In Chapter 3, Bigotta and Tonelli discuss laser cooling in fluoride single crystals. They detail the growth of high-purity rare-earth-doped BaY_2F_8 (BYF) and $LiYF_4$ (YLF), and show experimental results from optical refrigeration in such crystals doped with Yb. Chapter 4 deals with optical refrigeration in erbium-doped materials. The authors Fernandez, Garcia-Adeva and Balda provide a detailed description of the synthesis of chloride crystal KPb_2Cl_5 and fluorochloride glass CNBZn doped with erbium. These hosts have very low maximum phonon energies, and thus have the potential to exhibit very high quantum efficiencies. This chapter also presents experimental data on the laser cooling of these Er-doped materials at $\lambda \approx 850$ nm. This is quite interesting, as it corresponds to a transition involving the ground state and the $^4I_{9/2}$ manifold, which is the second excited state. The authors also discuss the role of excited state absorption and upconversion in the laser cooling process of Er-doped systems.

Mills and Buchwald (Chapter 5) present a thorough analysis of the numerous practical issues involved in realizing an optical refrigerator based on rare-earth-doped materials. In particular, they consider a cooler based on Yb:ZBLAN and provide modeling results that include pump saturation, pump circulation in a nonresonant cavity, fluorescence shielding, and thermal link considerations.

Chapters 6 and 7 focus on laser cooling in semiconductors. Chapter 1 gave an overview of the macroscopic analysis and experimental issues in this field. Chapters 6 and 7 present rigorous theoretical calculations that illustrate the interplay of the physical processes involved in the laser cooling of semiconductors and to explore how the materials can be adjusted to optimize efficiency and operating temperatures. In Chapter 6, Rupper, Kwong and Binder present a comprehensive microscopic theory for absorption and luminescence in a direct-gap semiconductor under the pertinent condition of a partially ionized exciton gas. The authors also extend their analysis to 2D (quantum wells) as well as to doped bulk semiconductors. In Chapter 7, Khurgin addresses a number of important issues pertaining to laser cooling in semiconductors. In particular, he considers how to engineer the density of states, phonon-assisted absorption in the band-tail, cooling in type II quantum wells, photonic bandgap structures, and the escape of luminescence by means of surface plasmon coupling.

In Chapter 8, Mungan reviews the concepts and history of the thermodynamics of fluorescent cooling. He discusses how the entropy and energy of beams of radiation are related. Mungan uses these results to calculate the ideal coefficient of performance for laser cooling and discusses how real-world effects reduce the efficiency. He then examines important practical topics such as radiation-balanced lasing, in which the heat generated by lasing is compensated for by fluorescent cooling, and the recycling of output optical energy into the input in order to increase the cooling efficiency.

In short, we hope that this book will serve its purpose as a major collection of the most significant findings to date in this relatively young yet thriving area of research. While the authors in this volume have attempted to provide forward-looking accounts of their areas of research, we have no doubt that the rapid and continuous progress in optical refrigeration will soon necessitate a new compendium of progress in the laser cooling of various solids and the development of optical refrigeration devices.

Albuquerque, NM
October 2008

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Optical Refrigeration in Solids: Fundamentals and Overview

Richard I. Epstein and Mansoor Sheik-Bahae

1.1
Basic Concepts

Optical refrigeration, or the cooling of solids with near-monochromatic light, is a discipline that was anticipated almost 80 years ago, decades before the invention of the laser. In 1929, the German physicist Peter Pringsheim (Figure 1.1) proposed the cooling of solids by fluorescence upconversion [3]. Because of the great advances that have been made in the use of lasers to cool and trap dilute gases of atoms and ions to extremely low temperatures, the term "laser cooling" is most often used in reference to this area of science. This is quite justified given its spectacular achievements, such as the creation of Bose–Einstein condensates and many related phenomena [1,2]. Nevertheless, optical refrigeration is itself a rapidly growing field; one that offers insights into the interaction of light with condensed matter, and has the potential to provide the basis for new types of cryogenic refrigeration. In the solid phase, thermal energy is largely contained in the vibrational modes of the lattice. In the laser cooling of solids, light quanta in the red tail of the absorption spectrum are absorbed from a monochromatic source, and then spontaneous emission of more energetic (blue-shifted) photons occurs. The extra energy is extracted from lattice phonons, the quanta of vibrational energy that are generated from heat. The removal of these phonons is therefore equivalent to cooling the solid. This process has also been termed "anti-Stokes fluorescence" and "luminescence upconversion" cooling.

Laser cooling of solids can be exploited to achieve an all-solid-state cryocooler [4–6], as conceptually depicted in Figure 1.2. The advantages of compactness, no vibrations, no moving parts or fluids, high reliability, and no need for cryogenic fluids have motivated intensive research. Spaceborne infrared sensors are likely to be the first beneficiaries, with other applications requiring compact cryocooling reaping the benefits as the technology progresses. A study by Ball Aerospace Corporation [7] shows that in low-power spaceborne operations, ytterbium-based optical refrigeration could outperform conventional thermoelectric and mechanical coolers in the temperature range 80 – 170 K. Efficient, compact semiconductor lasers can pump optical refrigerators. In many potential applications, the requirements

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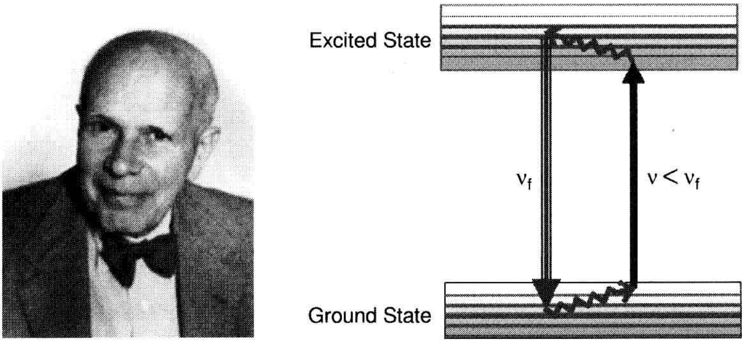

Figure 1.1 In 1929, Peter Pringsheim suggested that solids could cool through anti-Stokes fluorescence, in which a substance absorbs a photon and then emits one of greater energy. The energy diagram on the *right* shows one way in which this could occur. An atom with two broad levels is embedded in a transparent solid. The light source of frequency $h\nu$ excites atoms near the top of the ground state level to the bottom of the excited state. Radiative decays occurring after thermalization emit photons with average energy $h\nu_f > h\nu$.

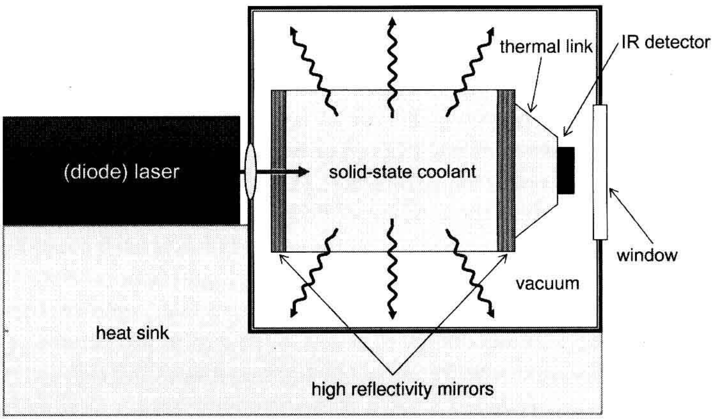

Figure 1.2 Schematic of an optical refrigeration system. Pump light is efficiently generated by a semiconductor diode laser. The laser light enters the cooler through a pinhole in one mirror and is trapped by the mirrors until it is absorbed. Isotropic fluorescence escapes the cooler element and is absorbed by the vacuum casing. A sensor or some other load is connected in the *shadow region* of the second mirror. Figure 1.2 has been reproduced from [6].

on the pump lasers are not very restrictive. The spectral width of the pump light has to be narrow compared to the thermal spread of the fluorescence. A multimode fiber-coupled laser with a spectral width of several nanometers would be adequate. In an optical refrigerator, the cooling power is of the order 1% of the pump laser power. Only modest lasers are adequate for microcooling applications with a heat lift of mW. For larger heat lifts, correspondingly more powerful lasers are needed. In all cooling applications, the cooling element has to be connected to the device being cooled, the *load*, by a thermal link; see Figure 1.2. This link siphons heat