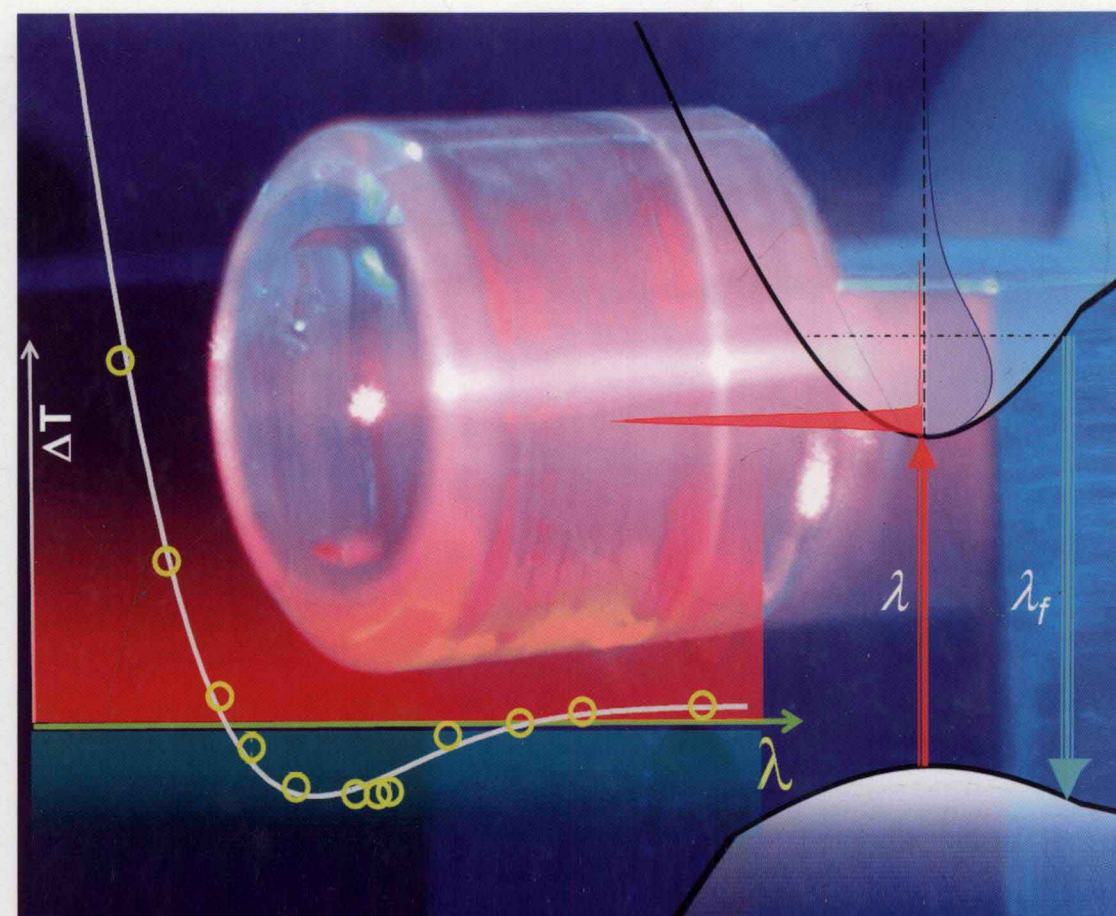


Edited by Richard I. Epstein and
Mansoor Sheik-Bahae

 WILEY-VCH

Optical Refrigeration

Science and Applications of Laser Cooling of Solids



Optical Refrigeration

Science and Applications of Laser Cooling of Solids

Edited by

Richard Epstein and Mansoor Sheik-Bahae



WILEY-VCH Verlag GmbH & Co. KGaA

The Editor

Richard Epstein

Los Alamos National Lab.
Los Alamos, NM, USA
Epstein@lanl.gov

Mansoor Sheik-Bahae

University of New Mexico
Department of Physics and Astronomy
Albuquerque, NM, USA
msb@unb.edu

Cover Illustration

Printed with kind
permission of the
editors.

All books published by Wiley-VCH are carefully produced. Nevertheless, authors, editors, and publisher do not warrant the information contained in these books, including this book, to be free of errors. Readers are advised to keep in mind that statements, data, illustrations, procedural details or other items may inadvertently be inaccurate.

Library of Congress Card No.: applied for British Library Cataloguing-in-Publication

Data: A catalogue record for this book is available from the British Library.

Bibliographic information published by the Deutsche Nationalbibliothek

The Deutsche Nationalbibliothek lists this publication in the Deutsche Nationalbibliografie; detailed bibliographic data are available on the Internet at
<<http://dnb.d-nb.de>>.

© 2009 WILEY-VCH Verlag GmbH & Co.
KGaA, Weinheim

All rights reserved (including those of translation into other languages).
No part of this book may be reproduced in any form by photoprinting, microfilm, or any other means nor transmitted or translated into a machine language without written permission from the publishers. Registered names, trademarks, etc. used in this book, even when not specifically marked as such, are not to be considered unprotected by law.

Typesetting le-tex publishing services oHG,
Leipzig

Printing Strauss GmbH, Mörlenbach

Binding Litges & Dopf GmbH, Heppenheim

Cover Design Adam Design, Weinheim

Printed in the Federal Republic of Germany
Printed on acid-free paper

ISBN 978-3-527-40876-4

Optical Refrigeration

Edited by
Richard Epstein and
Mansoor Sheik-Bahae

Related Titles

Capper, P., Mauk, M. (eds.)

Liquid Phase Epitaxy of Electronic, Optical and Optoelectronic Materials

2007

ISBN 978-0-470-85290-3

Incropera, F. P., DeWitt, D. P., Bergman, T. L., Lavine, A. S.

Fundamentals of Heat and Mass Transfer

2006

ISBN 978-0-471-45728-2

Csele, M.

Fundamentals of Light Sources and Lasers

2004

ISBN 978-0-471-47660-3

Dinçer, I.

Refrigeration Systems and Applications

2003

ISBN: 978-0-471-62351-9

Weidemüller, M., Zimmermann, C. (eds.)

Cold Atoms and Molecules

Concepts, Experiments and Applications to Fundamental Physics

2009

ISBN 978-3-527-40750-7

Weidemüller, M., Zimmermann, C. (eds.)

Interactions in Ultracold Gases From Atoms to Molecules

2003

ISBN 978-3-527-40389-9

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

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

Mansoor Sheik Bahae
Richard Epstein

List of Contributors

Stefano Bigotta

INFN
Sezione di Pisa
NEST-CNR
Università di Pisa
Dipartimento di Fisica
Largo Bruno Pontecorvo 3
56127 Pisa
Italy

Richard Epstein

Los Alamos National Laboratory
MS D466
Los Alamos, NM 87545
USA

Markus P. Hehlen

Los Alamos National Laboratory
Mail Stop J565
Los Alamos, NM 87545
USA

Gary Mills

Ball Aerospace & Technologies Corp.
1600 Commerce Street
Boulder, CO 80301
USA

Mauro Tonelli

INFN
Sezione di Pisa
NEST-CNR
Università di Pisa
Dipartimento di Fisica
Largo Bruno Pontecorvo 3
56127 Pisa
Italy

Joaquin Fernandez

University of the Basque Country
Applied Physics Department I
Escuela Superior de Ingenieros
Alda. de Urquijo s/n
48013 Bilbao
Spain

Carl E. Mungan

United States Naval Academy
Physics Department
572C Holloway Road
Annapolis, MD 21402-5002
USA

Rolf Binder

University of Arizona
College of Optical Sciences/Department
of Physics
1630 East University Boulevard
Tucson, AZ 85721
USA

Jacob Khurgin

Johns Hopkins University
Department of Electrical and Computer
Engineering
315 Barton Hall
3400 N. Charles Street
Baltimore, MD 21218
USA

Mansoor Sheik-Bahae

University of New Mexico
Department of Physics and Astronomy
800 Yale Blvd. MSC07 4220
Albuquerque, NM, 87131
USA

Angel Garcia-Adeva

University of the Basque Country
Applied Physics Department I
Escuela Superior de Ingenieros
Alda. de Urquijo s/n
48013 Bilbao
Spain

Rolindes Balda

University of the Basque Country
Applied Physics Department I
Escuela Superior de Ingenieros
Alda. de Urquijo s/n
48013 Bilbao
Spain

Mel Buchwald

Buchwald Consulting
Santa Fe, NM 87501
USA

Greg Rupper

University of Arizona
College of Optical Sciences
1630 East University Boulevard
Tucson, AZ 85721
USA

Nai H. Kwong

University of Arizona
College of Optical Sciences
1630 East University Boulevard
Tucson, AZ 85721
USA

Acknowledgments

We wish to thank our research groups (past and present) at the University of New Mexico and Los Alamos National Laboratory, as well as our numerous colleagues who have been instrumental in the progress of the research that has culminated to the publication of this book.

We also thank NASA, the US Department of Energy, and the Air Force Office of Scientific Research (AFOSR) for supporting optical refrigeration research. We are especially grateful to Dr. Charlie Stein (Air Force Research Lab) and Dr. Kent Miller (at AFOSR) for their continued and enthusiastic support of this research program.

Contents

Preface IX

1 Optical Refrigeration in Solids: Fundamentals and Overview 1

Richard I. Epstein and Mansoor Sheik-Bahae

- 1.1 Basic Concepts 1
- 1.2 The Four-Level Model for Optical Refrigeration 4
- 1.3 Cooling Rare-Earth-Doped Solids 7
- 1.4 Prospects for Laser Cooling in Semiconductors 12
- 1.5 Experimental Work on Optical Refrigeration
in Semiconductors 21
- 1.6 Future Outlook 26
- References 28

2 Design and Fabrication of Rare-Earth-Doped Laser Cooling Materials 33

Markus P. Hehlen

- 2.1 History of Laser Cooling Materials 33
- 2.2 Material Design Considerations 36
 - 2.2.1 Active Ions 37
 - 2.2.1.1 Rare-Earth Ions for Laser Cooling 37
 - 2.2.1.2 Active Ion Concentration 39
 - 2.2.2 Host Materials 40
 - 2.2.2.1 Multiphonon Relaxation 40
 - 2.2.2.2 Chemical Durability 42
 - 2.2.2.3 Thermal and Thermomechanical Properties 42
 - 2.2.2.4 Refractive Index 43
 - 2.2.3 Material Purity 45
 - 2.2.3.1 Vibrational Impurities 45
 - 2.2.3.2 Metal-Ion Impurities 46
- 2.3 Preparation of High-Purity Precursors 48
 - 2.3.1 Strategies for Preparing High-Purity Precursors 48
 - 2.3.2 Process Conditions 50
 - 2.3.2.1 Purity of Commercial Precursors 50

Optical Refrigeration. Science and Applications of Laser Cooling of Solids.

Edited by Richard Epstein and Mansoor Sheik-Bahae

Copyright © 2009 WILEY-VCH Verlag GmbH & Co. KGaA, Weinheim

ISBN: 978-3-527-40876-4

2.3.2.2	Process Equipment	50
2.3.2.3	Clean Environment	51
2.3.3	Material Purification	51
2.3.3.1	Filtration and Recrystallization	51
2.3.3.2	Solvent Extraction Using Chelating Agents	52
2.3.3.3	Fluorination and Drying in Hydrogen Fluoride Gas	54
2.3.3.4	Sublimation and Distillation	55
2.3.3.5	Electrochemical Purification	57
2.3.4	Determination of Trace Impurity Levels	57
2.4	Glass Fabrication	59
2.4.1	Glass Formation in ZrF_4 Systems	59
2.4.2	ZBLAN Glass Fabrication	62
2.4.2.1	Melting of the Starting Materials	62
2.4.2.2	Evaporative Losses	63
2.4.2.3	Dissolution and Homogenization	63
2.4.2.4	Optimum Rate of Cooling	63
2.4.2.5	Viscosity for Casting	64
2.4.2.6	Typical Glass Fabrication Parameters	64
2.4.3	Fluoride, Chloride, and Sulfide Glass Fabrication	65
2.5	Halide Crystal Growth	65
2.6	Promising Future Materials	66
2.6.1	Simplified Fluoride Glasses	67
2.6.2	Fluoride Crystals	67
2.6.3	Chloride and Bromide Crystals	68
	References	68

3 Laser Cooling in Fluoride Single Crystals 75

Stefano Bigotta and Mauro Tonelli

3.1	Introduction	75
3.2	Physical Properties	77
3.3	Experimental	78
3.3.1	Growth Apparatus	78
3.3.2	Spectroscopic Setup	80
3.3.3	Cooling Setup	81
3.4	Spectroscopic Analysis	83
3.5	Cooling Results	87
3.5.1	Cooling Potential	87
3.5.2	Bulk Cooling	89
3.6	Conclusion	93
	References	94

4 Er^{3+} -Doped Materials for Solid-State Cooling 97

Joaquin Fernandez, Angel Garcia-Adeva and Rolindes Balda

4.1	Low Phonon Energy Materials	97
4.1.1	KPb_2Cl_5 Crystal	98
4.1.2	Fluorochloride Glasses	101

4.2	Internal Cooling Measurements	101
4.3	Bulk Cooling Measurements	105
4.4	Influence of Upconversion Processes on the Cooling Efficiency of Er^{3+}	108
4.4.1	Spectroscopic Grounds: Upconversion Properties of Er^{3+} Under Pumping in the $^4\text{I}_{9/2}$ Manifold	108
4.4.2	A Phenomenological Cooling Model Including Upconversion	111
	References	114
5	Laser Refrigerator Design and Applications	117
	<i>Gary Mills and Mel Buchwald</i>	
5.1	Introduction	117
5.2	Modeling	119
5.3	Modeling Results	121
5.4	Design Issues	124
5.5	Mirror Heating	129
5.6	Applications	133
5.6.1	Comparison to Other Refrigeration Technologies	133
5.6.2	Vibration	133
5.6.3	Electromagnetic and Magnetic Noise	134
5.6.4	Reliability and Lifetime	134
5.6.5	Ruggedness	134
5.6.6	Cryocooler Mass and Volume	134
5.6.7	Efficiency and System Mass	134
5.6.8	Cost	136
5.7	Microcooling Applications	136
	References	138
6	Microscopic Theory of Luminescence and its Application to the Optical Refrigeration of Semiconductors	139
	<i>Greg Rupper, Nai H. Kwong and Rolf Binder</i>	
6.1	Introduction	139
6.2	Microscopic Theory of Absorption and Luminescence	141
6.3	Cooling Theory	151
6.4	Cooling of Bulk GaAs	153
6.5	Cooling of GaAs Quantum Wells	159
6.6	Cooling of Doped Bulk Semiconductors	162
6.7	Conclusion	164
	References	165
7	Improving the Efficiency of Laser Cooling of Semiconductors by Means of Bandgap Engineering in Electronic and Photonic Domains	169
	<i>Jacob B. Khurgin</i>	
7.1	Introduction	169

7.2	Engineering the Density of States Using Donor–Acceptor Transitions	171
7.3	Refrigeration Using Phonon-Assisted Transitions	174
7.4	Laser Cooling Using Type II Quantum Wells	180
7.5	Photonic Bandgap for Laser Cooling	186
7.6	Novel Means of Laser Cooling Using Surface Plasmon Polaritons	189
7.7	Conclusions	193
	References	194
8	Thermodynamics of Optical Cooling of Bulk Matter	197
	<i>Carl E. Mungan</i>	
8.1	Introduction	197
8.2	Historical Review of Optical Cooling Thermodynamics	198
8.3	Quantitative Radiation Thermodynamics	204
8.4	Ideal and Actual Performance of Optical Refrigerators	214
8.5	Closing Remarks	225
	References	230
	Index	233

1

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

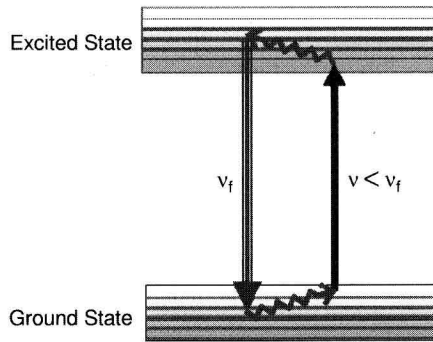


Figure 1.1 In 1929, Peter Pringsheim suggested that solids could cool through anti-Stokes fluorescence, in which a substance absorbs a photon and then emits one of greater energy. The energy diagram on the *right* shows one way in which this could occur. An atom with

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 $h\nu_f > h\nu$.

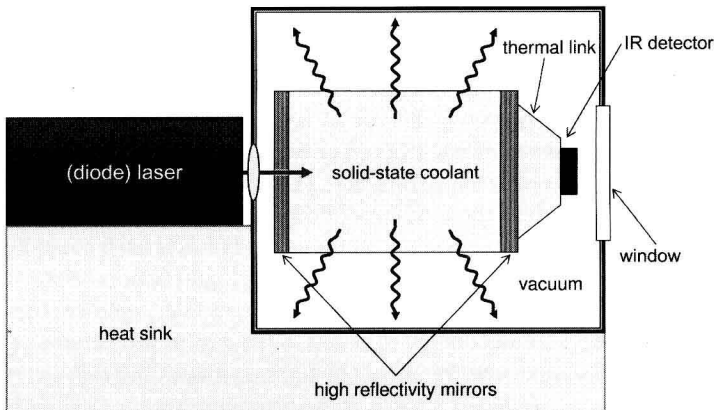


Figure 1.2 Schematic of an optical refrigeration system. Pump light is efficiently generated by a semiconductor diode laser. The laser light enters the cooler through a pinhole in one mirror and is trapped by the mirrors until it is absorbed. Isotropic fluorescence

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