Bahman Zohuri

Thermal Effects of High Power Laser Energy on Materials

Springer

Thermal Effects of High Power Laser Energy on Materials

Bahman Zohuri

Thermal Effects of High Power Laser Energy on Materials

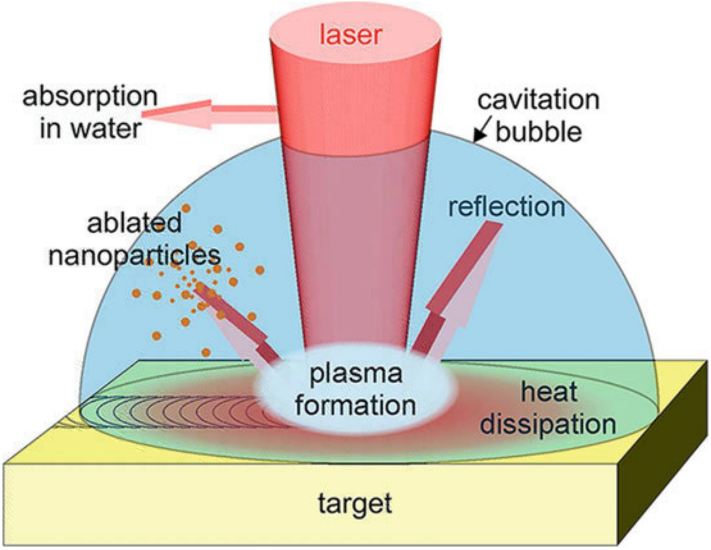
Springer

Bahman Zohuri
Galaxy Advanced Engineering Inc.
Albuquerque, NM, USA

ISBN 978-3-030-63063-8 ISBN 978-3-030-63064-5 (eBook)
https://doi.org/10.1007/978-3-030-63064-5

© The Editor(s) (if applicable) and The Author(s), under exclusive license to Springer Nature Switzerland AG 2021
This work is subject to copyright. All rights are reserved by the Publisher, whether the whole or part of the material is concerned, specifically the rights of translation, reprinting, reuse of illustrations, recitation, broadcasting, reproduction on microfilms or in any other physical way, and transmission or information storage and retrieval, electronic adaptation, computer software, or by similar or dissimilar methodology now known or hereafter developed.
The use of general descriptive names, registered names, trademarks, service marks, etc. in this publication does not imply, even in the absence of a specific statement, that such names are exempt from the relevant protective laws and regulations and therefore free for general use.
The publisher, the authors, and the editors are safe to assume that the advice and information in this book are believed to be true and accurate at the date of publication. Neither the publisher nor the authors or the editors give a warranty, expressed or implied, with respect to the material contained herein or for any errors or omissions that may have been made. The publisher remains neutral with regard to jurisdictional claims in published maps and institutional affiliations.

This Springer imprint is published by the registered company Springer Nature Switzerland AG
The registered company address is: Gewerbestrasse 11, 6330 Cham, Switzerland


laser
absorption in water
cavitation bubble
ablated nanoparticles
reflection
plasma formation
heat dissipation
target

This book is dedicated to my son Sasha, grandson Dariush, and my granddaughter Donya.

Preface

In this book, a tutorial discussion of the response of materials to laser radiation is presented, emphasizing simple, intuitive models. Topics discussed include optical reflectivity of metals at infrared (IR) wavelengths, laser-induced heat flow in materials, the effects of melting and vaporization, the impulse generated in materials by pulsed radiation, and the influence of the absorption of laser radiation in the blow-off region in front of the irradiated material.

The book aims to investigate the relations existing between the thermal parameters of simple metals and to check these relations based on available experimental data. This book also looks at the characteristics of materials and their prosperities, so one can investigate and perform theoretical analysis from heat conduction perspective mathematically.

The motivation of this investigation is to discover the constancy of a certain combination of thermal parameters, which is a mathematical condition for the linearization of one-dimensional, nonlinear, partial differential equation (PDE) of heat conduction. By solving these PDEs either numerically or to find a close solution by methods such as perturbation theory, Laplace transformation, or in some cases, asymptotic methods, and dimensional analysis. Using the Eulerian or Lagrangian approach, the solutions to boundary conditions and heat conduction problems in materials can be obtained.

The relationship of the above-mentioned combination of thermal parameters to results derived from the theory of solids was investigated, and applications of the resulting linearized or nonlinearized equations to problems in heat conduction are considered.

In this book we also have introduced commercially available and unclassified computer codes that deal with the responses of materials to laser radiation. Codes like PUFF-TFT, MOM, Asthma, ACE, and others are well described, and their capabilities are well introduced. Most of these codes were developed under some sort of government contracts during the era of Strategic Defense Initiative (SDI) in the past, and presently commercial and defense companies have them under development.

Chapter 1 of the book gives detailed descriptions of high-power laser energy. It covers the high-power laser and its energy definition. This chapter presents a tutorial discussion of the material responses to high-power laser energy radiations, with emphasis on simple, intuitive models. The topics discussed include optical reflectivity of metals at infrared (IR) wavelengths, laser-induced heat flow in materials, the effects of melting and vaporization, the impulse generated in materials by pulsed radiation, and the influence of the absorption of laser radiation in the blow-off region in front of the irradiated material.

Chapter 2 covers the material characteristics and their properties, where in modern society we are surrounded by an amazing variety of materials. Most of the materials discussed in this book are solids that have been modified from their natural states to make them more suitable for practical applications. The materials we use have such an impact on our lifestyles that historical eras have been named after them. Ancient artifacts found by archeologists have been dated and analyzed to reveal the increasing sophistication of the manufacturing methods. Historians have shown that technological advancements created new tools for agriculture and new weapons for armies. Explorers established trade routes to redistribute raw materials and finished products. Modern culture is also influenced by the availability of new materials.

Chapter 3 is the touching base of heat conduction in solids from holistic science of physics and mathematical theory point of view. One of the major goals of physics and so as ours in the case of laser in particular and its interaction with materials is to understand the nature of light. Due to the complex nature of light, this goal is very difficult to achieve, but this complication means that light offers many opportunities for different applications including optical interferences and the responses of materials to laser radiation and its interaction with matter and specifically metallic materials. This leads to dealing with the heat conduction equation in a very complex form; therefore, we need to deal with heat transport from the aspect of *conduction*, *convection*, and *radiation.*

Then comes Chap. 4. We have covered an introduction to electromagnetics, so our reader would refresh their background in physics and electrical engineering, when it comes to an understanding of the responses of materials to laser radiations, covered in Chap. 5. In order to comprehend laser interaction with matter, one needs to have some basic knowledge of the electromagnetic field in addition to conduction of heat in solids that was described in the previous chapter. Moreover, a general understanding of electromagnetic wave equation and consequently its behavior is necessary when it comes to laser irradiation. Thus, the Maxwell's equations and the electric field of the electromagnetic wave, and in this chapter, we try to introduce all these at a very holistic wave and leave the granule aspect of it to the readers so they can refer themselves to more detailed related books.

Chapter 5 covers the topic of the responses of materials to high-power laser energy radiation. The word laser is an acronym for light amplification by stimulated emission of radiation, although its common usage today is its noun form—laser—rather than as its acronym, LASER. A laser is a device that creates and amplifies a narrow, intense beam of coherent light. Atoms emit radiation. We see it every day when the "excited" neon atoms in a neon sign emit light. Normally, they radiate their light in random directions at random times. The result is incoherent light—a technical term for what you would consider a jumble of photons going in all directions. The trick in generating coherent light, of a single or just a few frequencies going in one precise direction, is to find the right atoms with the right internal storage mechanisms and create an environment in which they can all cooperate—to give up their light at the right time and all in the same direction.

Chapter 6 talks about the laser surface processing, where we cover high-power laser (HEL) and its application in the military for the purpose of precession as well as in industries as a cutting tool. High-power lasers (HPLs) have been used to process materials to improve their wear resistance since the late 1960s. Laser surface processing encompasses established techniques, such as laser transformation hardening, which has achieved production-level capabilities, and techniques that are still in the development stage, such as laser cladding, an emerging viable alternative to other hard-facing processes, such as plasma deposition. The laser beam is a chemically clean light source that delivers a precisely controlled quantity of energy to localized regions. Hence, only those areas exposed to wear are processed for improvement in wear resistance. The laser beam is easily maneuvered by optical elements and can be adapted to automation. High-power densities and low interaction times result in rapid heating and cooling, which produces a shallow heat-affected zone, low distortion of the workpiece, and minimal deterioration of bulk properties. Rapid solidification effects produce refined and novel microstructures that result in improved properties.

Finally, Chap. 7 would cover existing computer codes that this author has been involved with either to improve them to a customized level for a particular application or to use them both in the military and industries.

In this chapter, we will study and explain most of the computer codes that were developed during the administration of President Reagan and his idea of Strategic Defense Initiative (SDI) during the period 1980–1990. In this regard, scientists were looking at developing some means of computation capabilities that would deal with x-ray deposition into the matter and interaction of thermal and hydrodynamics of high-power laser energy with matter. These codes, in particular, were developed under the auspices of the Department of Energy (DOE) by tasking the Air Force Research Laboratory (AFRL) in support of ground-based laser (GBL), space-based laser (SBL), as well as airborne laser (ABL) with its supporting component known as Relay Mirror Experiment (RME) in order to overcome the effects and impacts of thermal blooming during the transport of the above laser system through the Earth's atmosphere and be able to shoot down any target around the globe.

Albuquerque, NM, USA, 2016 Bahman Zohuri

Acknowledgments

I am indebted to the many people who aided, encouraged, and supported me beyond my expectations. Some are not around to see the results of their encouragement in the production of this book, yet I hope they know of my deepest appreciations. I especially want to thank my true close friends, to whom I am deeply indebted, who have continuously given their support without hesitation. They all have always kept me going in the right direction.

Above all, I offer very special thanks to my late mother and father and to my children, in particular, my son Sasha, my daughters Natasha and Natalie, as well as my grandson Dariush and my granddaughter Donya. They have provided constant interest and encouragement, without which this book would not have been written. Their patience with my many absences from home and long hours in front of the computer to prepare the manuscript are especially appreciated.

Contents

4 Introduction to Electromagnetism 81

5 Response of Materials to High-Power Laser Energy Radiation 147

About the Author

Bahman Zohuri currently works for Galaxy Advanced Engineering, Inc., a consulting firm that he started in 1991 when he left both the semiconductor and defense industries after many years of working as a chief scientist. After graduating from the University of Illinois in the field of physics and applied mathematics, he went to the University of New Mexico, where he studied nuclear engineering and mechanical engineering. He joined Westinghouse Electric Corporation, where he performed thermal hydraulic analysis and studied natural circulation in an inherent shutdown and heat removal system (ISHRS) in the core of a liquid metal fast breeder reactor (LMFBR) as a secondary fully inherent shutdown system for secondary loop heat exchange. All these designs were used in nuclear safety and reliability engineering for a self-actuated shutdown system. He designed a mercury heat pipe and electromagnetic pumps for large pool concepts of a LMFBR for heat rejection purposes for this reactor in 1978, for which he received a patent. He was subsequently transferred to the defense division of Westinghouse, where he oversaw dynamic analysis and methods of launching and controlling MX missiles from canisters. The results were applied to MX launch seal performance and muzzle blast phenomena analysis (i.e., missile vibration and hydrodynamic shock formation). Dr. Zohuri was also involved in analytical calculations and computations in the study of nonlinear ion waves in rarefying plasma. The results were applied to the propagation of so-called soliton waves and the resulting charge collector traces in the rarefaction characterization of the corona of laser-irradiated target pellets. As part of his graduate research work at Argonne National Laboratory, he performed computations and programming of multi-exchange integrals in surface physics and solid-state physics. He earned various patents in areas such as diffusion processes and diffusion furnace design while working as a senior process engineer at various semiconductor companies, such as Intel Corp., Varian Medical Systems, and National Semiconductor Corporation. He later joined Lockheed Martin Missile and Aerospace Corporation as a senior chief scientist and oversaw research and development (R&D) and the study of the vulnerability, survivability, and both radiation and laser hardening of different components of the Strategic Defense Initiative, known as Star Wars.

This included payloads (i.e., IR sensor) for the Defense Support Program, the Boost Surveillance and Tracking System, and Space Surveillance and Tracking Satellite against laser and nuclear threats. While at Lockheed Martin, he also performed analyses of laser beam characteristics and nuclear radiation interactions with materials, transient radiation effects in electronics, electromagnetic pulses, system-generated electromagnetic pulses, single-event upset, blast, thermo-mechanical, hardness assurance, maintenance, and device technology.

He spent several years as a consultant at Galaxy Advanced Engineering, Inc., serving Sandia National Laboratories, where he supported the development of operational hazard assessments for the Air Force Safety Center in collaboration with other researchers and third parties. Ultimately, the results were included in Air Force Instructions issued specifically for directed energy weapons operational safety. He completed the first version of a comprehensive library of detailed laser tools for airborne lasers, advanced tactical lasers, tactical high-energy lasers, and mobile/tactical high-energy lasers.

He also oversaw SDI computer programs, in connection with Battle Management C^3I and artificial intelligence, and autonomous systems. He is the author of several publications and holds several patents, such as for a laser-activated radioactive decay and results of a through-bulkhead initiator. He has published many books and articles with different publishers and publishing companies; they all can be found on amazon.com or researchgate.net as well as on the Internet if a search is performed under his name.

Chapter 1
High-Power Laser Energy

This chapter goes through high-power laser and its energy definition. This chapter presents a tutorial discussion of the material responses to high-power laser energy radiations, with emphasis on simple, intuitive models. Topics discussed include optical reflectivity of metals at infrared (IR) wavelengths, laser-induced heat flow in materials, the effects of melting and vaporization, the impulse generated in materials by pulsed radiation, and the influence of the absorption of laser radiation in the blow-off region in front of the irradiated material.

1.1 Introduction

Throughout this chapter, we will discuss high-power laser and its energy definition and all related applications from industrial and military applications. High-power lasers emit very high optical powers, as required for a number of applications such as laser material processing; material processing such as welding, cutting, drilling, soldering, marking, and surface modification; as well as weapon of directed energy dwelling with its target of interest as part of its military application. Other applications are also considered, such as large-scale laser displays (i.e., red, green, and blue (RGB) source), remote sensing (e.g., with Light Detection and Ranging, LiDAR), medical applications (e.g., surgery), military applications (e.g., antimissile weapons), fundamental science (e.g., particle acceleration), and laser-induced nuclear fusion (e.g., in the National Ignition Facility (NIF) project). Note that in principle LASER stands for Light Amplification by Stimulated Emission of Radiation.

B. Zohuri, *Thermal Effects of High Power Laser Energy on Materials*,
https://doi.org/10.1007/978-3-030-63064-5_1

Lasers with extreme high-power laser energies (HPLEs) are required for a number of applications such as:

- *Material processing* (i.e., welding, precision cutting, drilling, soldering, marking surface modification). Laser beam welding is dominant in the automotive industry. It is used in the area where large-volume production is required.

  The principle of laser beam welding equipment along with its advantages and disadvantages are described as below.

  Laser beam welding (LBW) is a fusion welding process in which two metal pieces are joined together by the use of laser. The laser beams are focused to the cavity between the two metal pieces to be joined. The laser beams have enough energy and when it strikes the metal pieces produce heat that melts the material from the two metal pieces and fills the cavity. After cooling a strong weld is formed between the two pieces.

  It is a very efficient welding process and can be automated with robotics machinery easily. This welding technique is mostly used in the automotive industry.

  It works on the principle that electrons of an atom get excited by absorbing some energy. And then after some time when it returns back to its ground state, it emits a photon of light. The concentration of this emitted photon is increased by stimulated emission of radiation, and we get a high-energy concentrated laser beam.

  As Fig. 1.1 illustrates, the main parts of a laser welding equipment and beam welding are:

  1. **Laser machine:** It is a machine that is used to produce a laser for welding. The main components of the laser machine are shown in Fig. 1.1.
  2. **Power source:** A high-voltage power source is applied across the laser machine to produce a laser beam.
  3. **CAM:** It is a computer-aided machining in which the laser machine is integrated with the computers to perform the welding process. All the controlling action during the welding process by laser is done by CAM. It speeds up the welding process to a greater extent.
  4. **CAD:** It is called a computer-aided design. It is used to design the job for welding. Here computers are used to design the workpiece and how the welding is performed on it.
  5. **Shielding gas:** A shielding gas may be used during the welding process in order to prevent the welding processes from oxidation.

The types of lasers that are used in welding industry mainly are as follows:

1. **Gas lasers:** It uses mixtures of gases as a lasing medium to produce laser. Mixtures of gases such as nitrogen, helium, and CO_2 are used as the lasing medium.
2. **Solid-state laser:** it uses several solid media such as synthetic ruby crystal (chromium in aluminum oxide), neodymium in glass (Nd:glass), and neodymium in yttrium aluminum garnet (Nd:YAG, most commonly used).

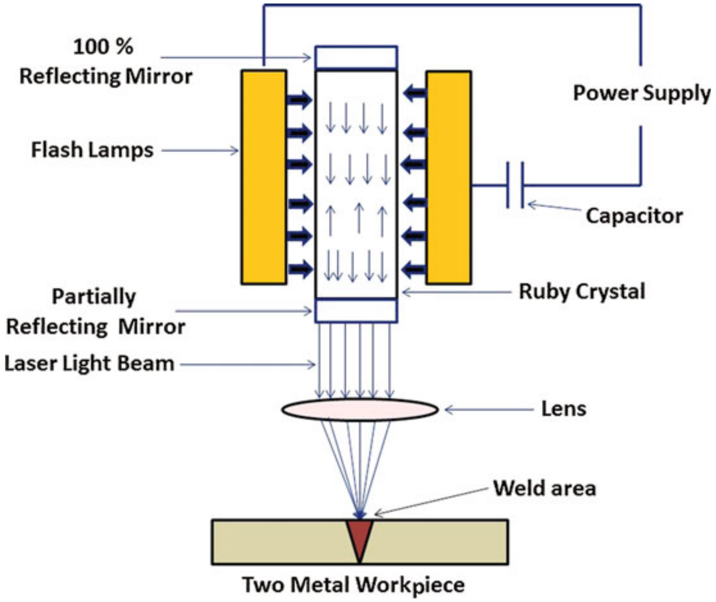


Fig. 1.1 Laser Beam Welding Equipment. (*Courtesy of* theweldingmaster.com)

3. **Fiber laser:** The lasing medium in this type of laser is optical fiber itself.

The characteristics of laser beam welding could be listed as follows:

1. The power density of laser beam welding is high. It is of the order 1 MW/cm^2. Because of this high energy density, it has small heat-affected zones. The rate of heating and cooling is high.
2. The laser beams produced are coherent (having the same phase) and monochromatic (i.e., having the same wavelength).
3. It is used to weld smaller sizes spot, but the spot sizes can vary from .2 mm to 13 mm.
4. The depth of penetration of the LBW depends upon the amount of power supply and location of the focal point. It is proportional to the amount of power supply. When the focal point is kept slightly below the surface of the workpiece, the depth of penetration is maximized.
5. Pulsed or continuous laser beams are used for welding. Thin materials are weld by using millisecond pulses, and continuous laser beams are used for deep welds.
6. It is a versatile process because it is capable of welding carbon steels, stainless steel, HSLA steel, aluminum, and titanium. Due to the high cooling rate, the problem of cracking is there when welding high-carbon steels.
7. It produces high-quality weld.
8. This welding process is the most popular in the automotive industry.

As per Fig. 1.1, laser welding typically works in the following steps:

- First, the setup of the welding machine at the desired location (in between the two metal pieces to be joined) is done.
- After setting it up, a high-voltage power supply is applied to the laser machine. This starts the flashlamps of the machine, and it emits light photons. The energy of the light photon is absorbed by the atoms of ruby crystal and electrons excited to their higher energy level. When they return back to their ground state (lower energy state), they emit a photon of light. This light photon again stimulates the excited electrons of the atom and produces two photons. This process continues, and we get a concentrated laser beam.
- This high concentrated laser beam is focused to the desired location for the welding of the multiple pieces together. Lens is used to focus the laser to the area where welding is needed. CAM is used to control the motion of the laser and workpiece table during the welding process.
- As the laser beam strikes the cavity between the two metal pieces to be joined, it melts the base metal from both the pieces and fuses them together. After solidification, we get a strong weld.
- This is how a laser beam welding works.

The advantages and disadvantages of the laser welding tool are listed below.

Advantages

- It produces high weld quality.
- LBW can be easily automated with robotic machinery for large-volume production.
- No electrode is required.
- No tool wears because it is a non-contact process.
- The time taken for welding thick section is reduced.
- It is capable of welding areas which are not easily accessible.
- It has the ability to weld metals with dissimilar physical properties.
- It can be weld through air and no vacuum is required.
- X-ray shielding is not required as it does not produce any X-rays.
- It can be focused on small areas for welding. This is because of its narrower beam of high energy.
- A wide variety of materials can be welded by using laser beam welding.
- It produces a weld of aspect ratio (i.e., depth-to-width ratio) of 10:1.

Disadvantages

- The initial cost is high. The equipment used in LBW has a high cost.
- High maintenance cost.
- Due to the rapid rate of cooling, cracks may be produced in some metals.
- High skilled labor is required to operate laser beam welding (LBW).
- The welding thickness is limited to 19 mm.
- The energy conversion efficiency in LBW is very low. It is usually below 10%.

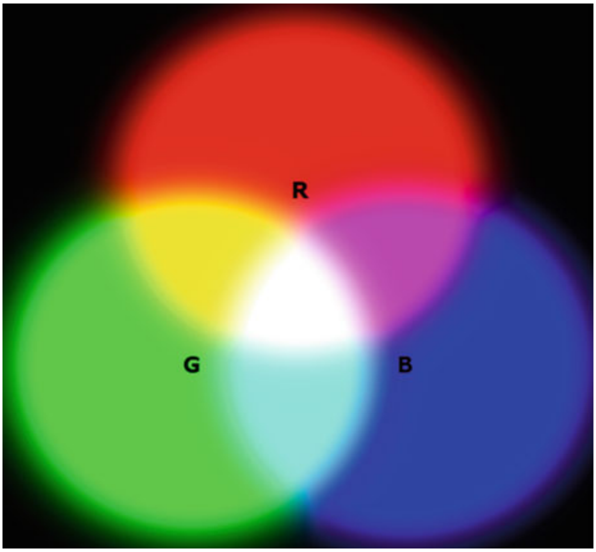


Fig. 1.2 Additive mixing of red, green, and blue light

Material processing with high-power lasers is the second largest segment of laser applications concerning global turnovers (after communications).

- **Large-scale laser displays** (i.e., red, green, blue (RBG) light sources, which are usually provided in the form of laser beams). An RGB source is a light source which emits at the same time red, green, and blue light. Such sources are required mainly for color display applications, for example, for large-screen video shows. A wide range of colors can be obtained by mixing different amounts of red, green, and blue light (*additive color mixing*; see Fig. 1.2).

A possible combination of wavelengths is 630 nm for red, 532 nm for green, and 465 nm for blue light. As Fig. 1.2, illustrates, superimposing inputs from three light sources can lead to white light, seen in the center. A wide range of other color tones could be achieved by mixing variable intensities of those contributions.

Many currently used projection displays ("beamers") are based on an *arc lamp*, combined with various color *filters*. While an arc lamp is much cheaper than a *laser* source of comparable output power, it does not allow for a high *wall-plug efficiency*, it has a limited lifetime, and the poor spatial *coherence* of the output imposes restrictions on the achievable image quality. Also, the available color space is not very large. Therefore, laser sources are under investigation that could offer a wider color space, much better spatial coherence (*beam quality*), and higher power efficiency. Such RGB laser sources emit light in the form of *laser beams*—either one beam for each color or all colors combined in one beam.

There are special RGB sources which can be used for stereoscopic displays, called 6P RGB sources. For each of the red, green, and blue colors, they have two spectral components which differ in wavelength, e.g., by 20 nm. For viewing, one

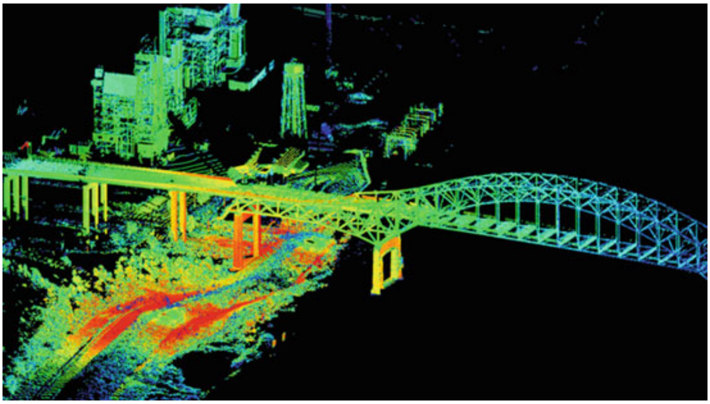


Fig. 1.3 Light Detection and Ranging (LiDAR)—GIS Lounge. (Source: USGS)

can then use special filter glasses which transmit only one set of wavelengths (R1, G1, B1) for the left eye and another set (R2, G2, B2) for the right eye. That way, one can produce independent images for the two eyes [1].

- **Remote sensing** (e.g., LiDAR). The acronym LiDAR stands for, basically, in principle, Light Detection and Ranging. LiDAR was originally understood as *laser radar* but is nowadays taken as an acronym meaning *Light Detection and Ranging*, which is somewhat more general (Fig. 1.3). It can be used for the creation of three-dimensional images based on *distance measurements*, e.g., with the *time-of-flight method*. In other cases, one measures other quantities such as the concentration of substances in air or wind velocities [2].

The capitalization of the term LiDAR is not consistent in the literature. Many authors simply write *lidar* (just like *radar*), although for acronyms full capitalization is more common.

LiDAR's first application was in the 1960s and came soon after the invention of lasers. Used in combination with radar, LiDAR was originally used in atmospheric studies to measure clouds by the National Center for Atmospheric Research. LiDAR later became more known by the public when the Apollo 15 mission used it to map the surface of the moon more accurately than ever before.

LiDAR has many other practical applications including mapping crop yields in agriculture, mapping terrestrial and extraterrestrial bodies, studying the atmosphere, and contributing to military technology. LiDAR is also used to detect objects underground and is vitally important for archeologists. LiDAR can find previously unmapped or unknown fault lines contributing to localized earthquakes as well as faults in building structures.

Also bear in mind that there exists equipment known as Laser Radar (LADAR) that stands for Laser Detection And Ranging as well. LADAR systems use light to determine the distance of an object, as illustrated in Fig. 1.4.

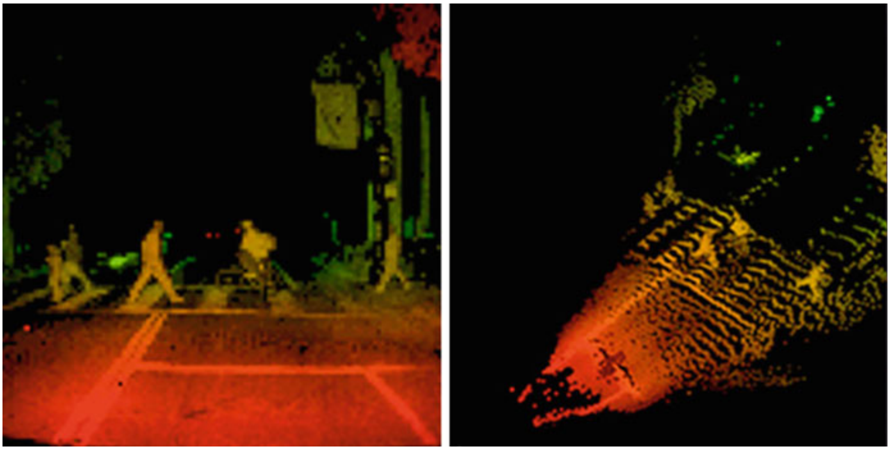


Fig. 1.4 LADAR Images. (Source: US Army provided by short-wave infrared (SWIR) camera of www.swirconops.com)

Note that in Fig. 1.4, on the left is a LADAR image from the front of a vehicle stopped at a crosswalk in Santa Barbara, CA. On the right is the same LADAR data “viewed” from an overhead location highlighting the 3-D nature of the data collected.

Many short-wave infrared (SWIR) camera capabilities are considered sensitive. If you would like to learn more about SWIR capabilities for the military, you can register at a special website, www.swirconops.com. You must be a US Government employee or a USG contractor and be a US Citizen to access this site.

Military application of SWIR presently is utilized in tracking of rocket and missile launches, flight paths, and intercept.

Visible and thermal tracking of rockets and missiles benefits from the addition of short-wave infrared (SWIR) cameras. Visible cameras suffer from atmospheric distortion and haze over long distances, while imaging with the short-wave infrared cuts through the interferences. Visible cameras only see the hottest portions of the rocket plume and have difficulty following missiles over long distances or bright ambient day lighting. The hot gases, however, are much more visible to SWIR and thermal cameras (also known as mid- and long-wave infrared cameras).

The thermal cameras easily see the thermal plume, but they lack the ability to see the hard body or debris because they aren’t equally as hot. Nor can they “see” with the resolution of SWIR cameras. The InGaAs-based SWIR cameras share the visible camera’s ability to use glass based optics, requiring less expensive lens solutions. SWIR cameras also operate with lower power and size than thermal cameras, allowing for more platform flexibility. Awaiting similar test confirmation is our new DR1 High Dynamic Range control algorithm, a hardware solution that will increase the ability of InGaAs cameras to extract additional imaging information from such high contrast scenes.

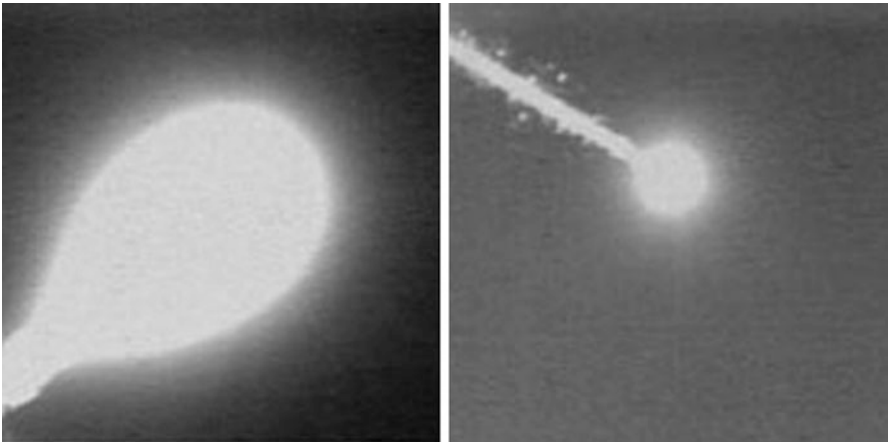


Fig. 1.5 Flying debris tracking. (Source: US Army provided by short-wave infrared (SWIR) camera of www.swirconops.com)

In the image below, on the left, a missile is launched into the air as a SWIR camera tracks its path. Hot debris is shown coming off of the plume. On the right, the descending missile is still visible to a SWIR camera even from many miles away. Flying debris can still be detected at this distance as demonstrated in Fig. 1.5.

Note that in Fig. 1.5, Sensors Unlimited offers video and high-frame rate InGaAs cameras with 320×256 or 640×512 formats that are ideal for integration on missile tracker systems or perimeter defense scanning for shoulder-fired rockets.

Founded in 1991 as an advanced research and development company, Sensors Unlimited quickly grew as a world leader in and innovator of indium gallium arsenide semiconductor technology. Tracking missile and rockets is only one of the many applications for our short-wave infrared technology; SUI products are also used for night vision, laser designation, and the tracking of lasers.

Many SWIR camera capabilities are considered sensitive. If you would like to learn more about SWIR capabilities for the military, you can register at a special website, www.swirconops.com. You must be a US Government employee or a USG contractor and be a US Citizen to access this site [3, 4].

Since the speed of light is well-known, LADAR can use a short-pulsed laser to illuminate a target and then time how long it takes the light to return. The advantage of LADAR over RADAR (radio detection and ranging) is that LADAR can also image the target at the same time determine the distance. This allows a 3-D view of the object in question. This provides long-range reconnaissance with greater fidelity and thus greater recognition range than other technologies.

Newer LADAR systems, with InGaAs detectors on board, can use eye-safe lasers (traditionally 1.55 or 1.57 microns) to minimize the users' eye damage, as well as eye damage to other combatants and non-combatants on the battlefield. In addition to eye safety concerns, these lasers are also used as night vision goggles and in older night vision technologies, allowing for the location of the detected object and the laser to be kept secret.

- **Medical applications** (e.g., surgery). There are various kinds of lasers which are applied for medical purposes. In most cases, they essentially do a kind of laser material processing, just on biological materials. In a few cases, laser light is used in other ways, for example, for triggering photochemical reactions.

Lasers are not only used for medical therapies but also for diagnostic purposes and for medical research. For example, there are methods of ocular imaging with optical coherence tomography (which may involve wavelength-swept lasers), laser microscopy, and laser spectroscopy, which all can be useful for planning treatments. Optogenetics is another important field in medical research which profits from laser technology.

Besides lasers, medical laser system may contain various other kinds of photonics and optics technology, e.g., frequency converters, photodetectors for monitoring purposes, cameras, and beam delivery systems.

Generally, medical laser systems need to fulfill relatively strict conditions. In particular, they need to be highly reliable, since a failure during a medical operation may have serious consequences. Their performance parameters must be well reproducible and precisely monitored during operation. Various legal conditions (e.g., fulfilling certain standards), which can substantially vary between countries, must be fulfilled before such lasers can be applied.

The following sections describe some typical applications of medical lasers. Note, however, that the article cannot completely cover the huge field of medical applications, with many new applications being under development [5].

1. **Lasers in Ophthalmology**

   Ophthalmology, i.e., the branch of medicine and surgery dealing with the diagnosis and treatment of problems of the eye, is a classical field of medical laser applications. This is essentially because the eye, including essential inner parts like the retina (the light-sensitive region), is well accessible by light, while other approaches, e.g., to the retina are difficult.
2. **Lasers in Dermatology**

   The skin is also a particularly accessible part for laser radiation, and various laser treatment methods have been developed for treatment of different skin conditions. For example, vascular and pigmented lesions can be treated, also scars and wrinkles. Further, lasers are frequently applied for the removal of tattoos and for hair removal.
3. **Lasers in Dentistry**

   A common application is the preparation of cavities in the context of curing caries. This can be done with short pulses from a Q-switched Er:YAG laser. Compared with conventional drilling, this procedure may incur less pain.

   There are various other laser applications in dentistry, which concern either the hard tissue (teeth) or soft tissues, e.g., for exposing unerupted or partially erupted teeth.
4. **Lasers in Urology**

   A popular method is the treatment of benign prostatic hyperplasia, which causes problems for many men. There are endoscopes containing optical fibers which allow minimally invasive operations, where high-power laser light, e.g., from laser diodes is used to ablate tissues. Compared with open operations, there are reduced risks of complications, and the recovery of the patient is quicker.

Laser lithotripsy has been developed for removing stones in the urinary tract. Different microscopic mechanisms can be used to break apart stones with intense laser pulses, such that the remaining small pieces can be easily washed out of the urinary tract. One mostly uses Q-switched holmium lasers emitting around 2.1 μm, a spectral region with good absorption in water. However, it is currently investigated whether the use of thulium fiber lasers could be advantageous due to advantages like a better beam quality and higher pulse repetition rates. The method appears to be a good alternative to extracorporeal shockwave lithotripsy with ultrasound waves.

Lasers are also used for treating urothelial tumors, prostate cancer, urolithiasis, and urinary tract strictures, for example.

5. **Lasers in General Surgery**

   Lasers may also be used in other kinds of surgery for cutting (*laser scalpel*), ablating, or cauterizing tissues. A wide range of laser types can in principle be used, including CO_2 lasers, diode lasers, fiber lasers, gas lasers, and excimer lasers. Both continuous-wave operation and pulsed operation can be useful.

   Typical advantages of laser surgery are that the affected tissue are automatically sterile and the tendency for bleeding is reduced through the effect of photocoagulation. However, there may also be disadvantages, such as a lack of haptic feedback and a low processing speed. In some cases, lasers need to be developed, e.g., with increased pulse repetition rates for faster processing.

- **Military applications** (e.g., directed-energy weapons). Directed-energy weapons are nothing new to mankind; historically the origin of such weapons began centuries ago when the famous Greek mathematician, physicist, engineer, inventor, and astronomer Archimedes of Syracuse used different mirrors to collect sunbeams and focused them on the Roman fleet in order to destroy enemy ships with fire. This is known as the Archimedes heat ray. Archimedes may have used mirrors acting collectively as a parabolic reflector to burn ships attacking Syracuse. The device was used to focus sunlight onto approaching ships, causing them to catch fire. Of course, the myth or reality of the Archimedes heat ray still is questionable, but with the help of a group of students from Massachusetts Institute of Technology, certain experiments were carried out with 127 1-foot (30 cm) square mirror tiles in October of 2005 that were focused on a mockup wooden ship at a range of about 100 feet (30 m). The flames broke out on a patch of the ship, but only after the sky had been cloudless and the ship had remained stationary for around 10 min. It was concluded that the device was a feasible weapon under these conditions.

The battles of tomorrow will be fought with different weapons that have more lethal effects and faster delivery systems. One of mankind's greatest achievements in the twentieth century is the ability to destroy the entire human race several times over. At this time of intensive arms, more money is invested in the next generation of

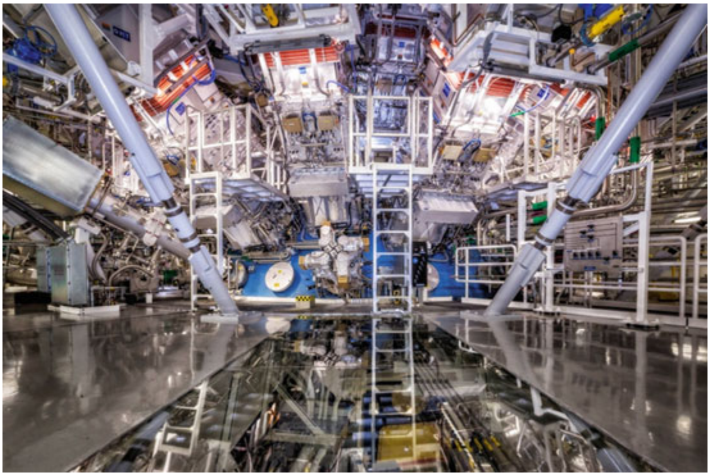


Fig. 1.6 Overview of the National Ignition (NIF) Facility

weapons. It is in the best interest of every citizen to be aware and able to make an informed judgment on the best possible direction for the arms race. Offensive or defensive weapons are a cruel reality that nevertheless must be addressed [6].

- **Laser-induced nuclear fusion** (e.g., National Ignition Facility (NIF)) project is taking advantages and process of the extreme conditions of matter that are encountered both in nature and in the laboratory, for example, in the center of stars and in relativistic collisions of heavy nuclei, now inertial confinement fusion (ICF), where a temperature of 10 °K and a pressure exceeding a billion atmospheres can be achieved (Fig. 1.6). A sound knowledge of the equation of state is a prerequisite for understanding processes of very high temperature and pressures, as noted in some recent developments [7, 8].

The National Ignition Fusion (NIF) experiment in Lawrence Livermore National Laboratory in California is a large laser-based inertial confinement fusion research device using a laser to confine fuel of D-T, in a pellet, as illustrated in Fig. 1.6.

Fundamental science (e.g., particle acceleration). At present the highest energy accelerators are all circular colliders, but both hadron accelerators and electron accelerators are running into limits. Higher-energy hadron and ion cyclic accelerators will require accelerator tunnels of larger physical size due to the increased beam rigidity.

For cyclic electron accelerators, a limit on practical bend radius is placed by synchrotron radiation losses, and the next generation will probably be linear accelerators 10 times the current length. An example of such a next-generation electron accelerator is the proposed 40-km-long International Linear Collider.

It is believed that plasma wakefield acceleration in the form of electron beam “afterburners” and standalone laser pulsers might be able to provide dramatic increases in efficiency over RF accelerators within two to three decades. In plasma wakefield accelerators, the beam cavity is filled with a plasma (rather than vacuum). A short pulse of electrons or laser light either constitutes or immediately precedes the particles that are being accelerated. The pulse disrupts the plasma, causing the charged particles in the plasma to integrate into and move toward the rear of the bunch of particles that are being accelerated. This process transfers energy to the particle bunch, accelerating it further, and continues as long as the pulse is coherent [9].

Energy gradients as steep as 200 GeV/m have been achieved over millimeter-scale distances using laser pulsers [10], and gradients approaching 1 GeV/m are being produced on the multi-centimeter scale with electron beam systems, in contrast to a limit of about 0.1 GeV/m for radio-frequency acceleration alone. Existing electron accelerators such as that of the Stanford Linear Accelerator Center (SLAC) could use electron beam afterburners to greatly increase the energy of their particle beams, at the cost of beam intensity. Electron systems in general can provide tightly collimated, reliable beams; laser systems may offer more power and compactness. Thus, plasma wakefield accelerators could be used—if technical issues can be resolved—to both increase the maximum energy of the largest accelerators and to bring high energies into university laboratories and medical centers.

Higher than 0.25 GeV/m gradients have been achieved by a dielectric laser accelerator, [11] which may present another viable approach to building compact high-energy accelerators [12]. Using femtosecond duration laser pulses, an electron accelerating gradient 0.69 Gev/m was recorded for dielectric laser accelerators [13]. Higher gradients of the order of 1 to 6 GeV/m are anticipated after further optimizations [14].

1.2 Heat Conduction in Simple Metals

Material processing with high-power lasers is the second largest segment of laser applications concerning global turnovers (after communications).

There is no commonly accepted definition of the property “high power”; in the context of laser material processing, it usually means multiple kilowatts or at least a few hundred watts, whereas for laser displays, some tens of watts may already be considered high. In some areas, this label is assigned simply for generating a significantly higher output power than other lasers based on the same technology; for example, some “high-powered” laser pointers emit a few hundred milliwatts, whereas ordinary laser pointers are limited to a few milliwatts.

Additional aspects come into play for pulsed lasers. For example, the peak power may be as important as the average output power for a Q-switched laser. Depending on the pulse repetition rate and pulse duration, the peak power may be very high even for a laser with a moderate average output power. Usually, a high average power and not only a high peak power is expected from a high-power laser.

Theoretically the relations that exist between the thermal parameters of simple metals can be investigated, and we can check these relations in more detail in the following chapters of this book. The motivation behind such investigation is the discovery of the constancy of a certain combination for the linearization of the one-dimensional, non-linear, partial differential equation of heat conduction. The relationship of the abovementioned combination of thermal parameters to result derivable from the theory of solid will also be investigated in further chapters, and applications of the resulting linearized equation to problems in heat conduction will be considered.

1.3 Technical Challenges

One of the technical challenges about producing a laser beam as a high-power energy is its generation. The generation of high optical power in lasers involves the following number of technical issues:

1. One requires one or several powerful pump sources. While lamp pumping was originally the only viable approach for most solid-state lasers, pumping with high-power laser diodes (diode bars or diode stacks) has become more and more widespread. Diode-pumped lasers now offer the highest output powers in continuous-wave operation. For very high pulse energies (e.g., tens of joules), lamp pumping is still more practical.
2. At least for long-term continuous-wave operation, a high wall-plug efficiency is an important economic factor. Unfortunately, various technical challenges (e.g., thermal effects; see below) tend to make it more difficult at very high power levels to achieve a good efficiency.
3. Even in a fairly efficient gain medium, a substantial fraction of the pump power is converted into heat, which can have a number of detrimental side effects. In the worst case, thermally induced stress leads to fracture of the laser crystal. High-power solid-state lasers also exhibit strong thermal lensing, making it substantially more difficult to achieve a high beam quality. In lasers with polarized output, depolarization loss often compromises the efficiency. Efficient heat removal and thermal management are therefore important issues, and additional measures (e.g., in the context of resonator design) are often required for coping with various kinds of thermal effects.
4. Particularly in Q-switched lasers, very high optical intensities can occur, which may lead to laser-induced damage of optics (such as laser mirrors), e.g., via laser-induced breakdown. Even if the optical intensities remain well below the damage threshold of all optical elements, tiny dust particles can provoke damage phenomena. It can therefore be essential to keep the laser setup very clean, e.g., by operating it in a sealed case which may be opened only in a clean room. In addition, it can be imperative to use precision optics with a high optical damage threshold.

5. Laser resonators with large effective mode areas tend to be sensitive to misalignment and vibrations of optical components. It can therefore be more challenging to achieve robust maintenance-free operation and a good beam pointing stability.

As it can be observed from the above points, to produce a high-quality high-power laser energy, we need to technically overcome these challenges [5].

1.4 Types of High-Power Lasers

There are several different types of high-power lasers.

- High-power *diode bars* and *diode stacks* have already been mentioned above as possible pump sources for *solid-state lasers*. They allow the generation of kilowatts of output power, but with a poor *beam quality*. For some applications, where beam quality is not essential, the direct use of high-power laser diodes (→*direct diode lasers*), e.g., for laser welding, soldering and brazing, cladding, and heat treatment, is an interesting option, offering a comparatively simple, compact, cost-effective, and energy-efficient solution.
- There are various types of lamp-pumped or diode-pumped solid-state bulk lasers. Rod lasers can be optimized for several kilowatts of output power, but diffraction-limited beam quality is possible only up to a few hundred watts (with significant efforts). Slab lasers can be developed for tens of kilowatts or more with relatively high beam quality. Thin-disk lasers easily generate hundreds of watts with diffraction-limited beam quality and have the potential to reach that even at power levels well above 10 kW. The power efficiency is usually fairly good.
- High-power fiber lasers and amplifiers can generate up to a few kilowatts with close to diffraction-limited beams and high power efficiency. With relaxed beam quality requirements, even significantly higher powers are possible. Strictly, such fiber devices are often not lasers, but master oscillator power amplifier (MOPA) configurations.
- Some gas lasers, e.g., CO_2 lasers and excimer lasers, are also suitable for hundreds or thousands of watts of output power. They typically operate in different other regions than solid-state lasers, e.g., in the mid-infrared or ultraviolet region.
- There are chemical lasers with multi-kilowatt or even megawatt output powers, explored e.g., in the context of antimissile weapons.

A perhaps not very practical but theoretically very interesting high-power laser concept is that of the radiation-balanced laser. Here, heat generation in the gain medium is essentially eliminated by optical refrigeration.

An aspect of great importance for further laser development is that of *power scaling*, based on certain power-scalable laser architectures. Even for non-power-scalable laser types, it can be very helpful to understand the scaling properties of various parts or techniques.