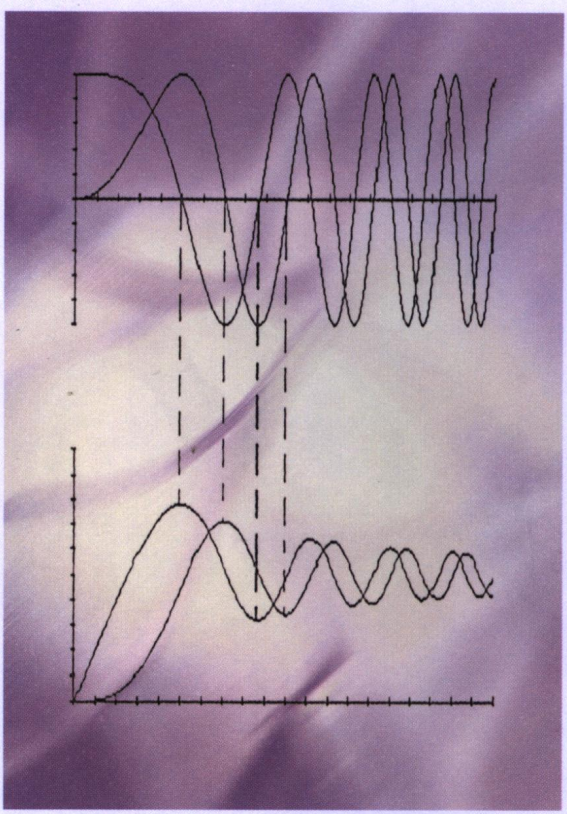
应用物理学丛书

激光的衍射及热作用计算



李俊昌 著

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2002

内 容 简 介

本书是作者多年以来从事激光变换及激光与金属材料相互热作用的理论模拟及实验研究的成果总结.主要内容包括光波电磁理论基础、标量衍射理论、衍射积分在空域的计算、衍射积分在频域的快速计算、衍射场空间追迹及等效傍轴光学系统、高斯光束和激光谐振腔及激光束参数讨论、激光变换光学系统、非熔凝态激光与物质相互热作用的半解析计算、激光与物质相互热作用复杂过程的数学表述.

本书适合于光学、激光加工、机械制造、材料等专业大学师生及技术人员阅读、参考.

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《应用物理学丛书》出版说明

1978年夏在庐山召开的中国物理学会年会("十年动乱"结束后的全国物理学界第一次大型学术会议)上,部分与会专家与学者经过充分酝酿和热烈讨论后一致认为,为了迎接科学春天的到来和追赶世界先进科学技术水平,有必要编辑出版一套《实验物理学丛书》,并组成以钱临照院士为主编,王淦昌等5位院士为副主编,王之江、王业宁等26位院士或专家为编委的《实验物理学丛书》编委会.

20年来,这套丛书在钱临照院士的主持下,通过编委们的积极工作(有的编委还亲自撰稿),先后出版了《实验的数据处理》、《X射线衍射貌相学》、《粒子与固体相互作用物理学》、《压电与铁电材料的测量》、《电介质的测量》、《物理技术在考古学中的应用》及《材料科学中的介电谱技术》等20部实验物理学著作.这些著作都是实验、科研和教学的系统总结,出版后受到读者的欢迎和好评,有不少被评为国家级、部级和院校级的优秀科技图书,如《实验的数据处理》一书获第一届全国优秀科技图书一等奖.这套丛书的陆续出版,在社会上引起较大影响,在科研、教学、经济建设和国防建设中发挥了积极的作用.

改革开放以来,我国在各个方面发生了翻天覆地的变化,经济体制由计划经济逐步转向社会主义市场经济,科学技术和教育也得到了空前的发展.为了适应社会主义市场经济的需要和满足社会的需求,我们决定对原丛书的出版宗旨、选题方向做相应的调整,重新组建编委会,并将原丛书更名为《应用物理学丛书》,使新丛书能在"科教兴国"和将科学技术转化为生产力的伟大实践中发挥更大的作用.

《应用物理学丛书》的出版宗旨和选题方向如下:

1. 密切联系当前科研、教学和生产的实验需要，介绍应用物理学各领域的基本原理、实验方法、仪器设备及其在相关领域中的应用，并兼顾有关交叉学科.

2. 反映国内外最新的实验研究与技术水平和发展方向，并注重实用性.

3. 以大专院校师生以及科研单位、国防部门、工矿企业的科研人员为对象，理论与实验紧密联系.

这套丛书将按照“精而准、系统化”的原则，力求保持并发展原《实验物理学丛书》已形成的风格和特色，多出书、出好书.

需要强调的是，《应用物理学丛书》将优先出版那些有助于将科学技术转化为生产力以及对社会和国民经济建设有重大作用和应用前景的著作.

我们坚信，在编委们的共同努力下，在广大科研和教学人员的积极参与和大力支持下，《应用物理学丛书》的出版将对我国科学技术和教育事业的持续发展发挥积极的作用！

《应用物理学丛书》编委会

前　言

激光的传输、变换及激光与物质的相互热作用，是强激光应用研究中涉及的基本课题. 1985 年以来，作者一直从事该领域的课题研究，在国外，与法国里昂应用科技学院（Institut National des Sciences Appliquée）、里昂中央理工大学（Ecole Centrale de Lyon）以及巴黎高等技术大学（Ecole Nationale Supérieure des Arts et Méties de Paris）保持了稳定的科研合作，承担过法国标致汽车公司技术开发部（PSA Etudes et Recherches）的研究项目和指导中法双方的博士生；在国内，先后完成过国家教委优秀青年教师基金、国家自然科学基金及云南省自然科学基金的项目. 在研究工作中，作者深切地体会到标量衍射理论、热传导理论及计算机技术在激光应用研究中发挥的重要作用. 作者对激光及激光与物质相互热作用的认识，基本上是在使用计算机模拟和解决实际问题中逐步形成的.

光波是电磁波. 按照标量衍射理论，光传播的宏观物理过程就是电磁波在空间的衍射过程. 当前，激光的应用几乎遍及经济建设及国防科研的每一个领域，如果要定量描述激光在应用研究中所起的作用，几乎都涉及到光波场的衍射计算. 然而，衍射问题通常只能表为难于求解的重积分，即使是已经十分了解标量衍射理论的科技工作者，要正确地完成衍射计算也不是一件容易的事. 近年来，计算机技术的飞速发展与计算机的普及应用为完成衍射计算提供了极大的方便. 如果能够从光传播的物理概念出发，通过对衍射积分的研究，结合计算机数值计算的特点，总结出一套模拟激光传播与变换过程的计算方法，必然能为相关专业的研究生及科技工作者提供方便. 这成为写作本书的主要原因.

激光与物质相互热作用受到较多不确定因素的影响，利用解

析计算公式准确模拟激光与物质相互热作用的过程十分困难，能够较好地模拟激光与物质相互作用物理过程的工作基本上只能通过纯数值计算完成.然而，庞杂的纯数值计算无论是计算时间和成本均很难为实际应用所承受，并且，计算模型基本上是对特定的问题设计的，将计算模型移植到同类研究中绝非易事.为简化研究，人们通常将激光假设为理想的基横模高斯光束或一些便于分析的光束形式，将激光照射对象视为热物性参数为常量的半无限大体，从而导出了一些便于计算的表达式.但是，由于简化研究作了许多与实际情况相距甚远的假设，研究结果通常不能直接为实际应用服务.研究快速可靠的计算方法，仍然是有效控制激光对物质热作用过程需要解决的基本课题.在国家及云南省自然科学基金的资助下，基于快速傅里叶变换技术及半解析分析的理论，作者提出了一些比较接近实验结果的快速计算方法.将这些工作整理成文，应能为国内相关专业的研究生及工程技术人员提供一个有益的参考.这成为写作本书的另一个重要原因.

因此，本书主要是研究激光传播、变换及激光与物质相互热作用的计算问题.并将书名定为《激光的衍射及热作用计算》.

由于经典电磁场理论是标量衍射理论的基础，为便于非光学专业的读者阅读本书，本书第一、二章对经典电磁场理论及标量衍射理论作了必要的介绍.众所周知，经典电磁场理论及标量衍射理论在100多年以前便已经形成，然而，只是在激光及计算机出现后，标量衍射理论才在应用研究中获得了瞩目的发展.它不但成为现代光通信及光信息处理的重要理论基础，而且，从经典的菲涅耳衍射积分出发，针对一些特定的问题，已经衍化出以柯林斯公式为代表的许多便于使用的衍射计算公式.在写作这两章的过程中，作者主要参考了近年来出版的几部专著，它们是：天津大学郁道银先生及浙江大学谈恒英先生所著的《工程光学》、四川大学吕百达先生的《强激光的传输与控制》以及1996年法国出版的Marie May，Anne-Marie Cazabat的专著“Optique”.

第三、四、五章总结了作者在空域及频域计算衍射积分的多种

方法，并结合实际介绍通过等效傍轴光学系统计算光波穿过离轴光学系统时衍射场的空间追迹方法.正确计算光的衍射，是光信息处理研究中一个最重要的内容.在这三章中，为证实所讨论的每一种方法的可行性，均给出了理论计算与实验测量进行比较的实例.具备科学计算与计算机编程基本知识的读者，根据书上所整理的计算公式，应能够重复得到所有的结果，并通过自己所编写的程序解决应用研究中涉及的问题.

由于衍射计算涉及到激光束参数的定义及测量，第六章利用衍射理论研究了高斯光束及一般光束参数的定义，简要介绍两种强激光功率密度分布检测的方法.

第七章阐述激光加工及热处理应用研究中一些典型的光束变换系统.本书讨论的衍射计算方法在这一章中得到了综合的应用.从这一章中，读者可以清楚地看出，标量衍射理论能够十分准确地计算相干光通过光学系统时光波场分布的空间变化过程.对于从事激光与物质相互作用研究的读者，可以对实际到达材料表面的光束强度分布形成较直观的概念.虽然所讨论的光学系统主要是针对工业激光加工及热处理的需要而提出的，但是，高技术应用研究中对强激光均匀化的研究遵循的是同样的原则和理论，所进行的讨论对从事强激光高技术应用研究的工作者也是有益的.

第八章介绍激光与物质相互热作用的半解析及快速傅里叶变换计算方法.这一章中，激光已经不再假定为理想化的分布形式，激光照射的对象也不再视为与实际情况相距甚远的半无限体.从热物性参数为常量的无限大介质热传导方程的解析解出发，引入多种形式的“像热源”处理边界问题，讨论了一些计算速度快，比较接近实际应用并得到实验支持的计算方法.对每一种计算方法均列出比较详细的计算公式及理论证明，并给出理论计算与实际测量的比较.

第九章是热作用纯数值计算方法的简要介绍及对一些较复杂的激光与物质相互作用物理过程的研究.在国际合作中，昆明理工大学陈庆华、伏云昌老师利用国外的实验条件在该研究领域进行

了十分有成效的研究.主要由这两位老师撰写的这一章中,读者可以了解到利用有限差分法求解热作用问题的基本方法及部分计算实例,了解到许多较复杂的激光与物质相互热作用问题的物理模型及数学表述方法.所提供的计算实例亦给出较详尽的计算公式,对相关专业的研究生及研究人员是非常有益的.

最后,在附录中简要介绍本书理论计算中涉及最多的傅里叶变换的基本知识及几个特殊函数.

作者非常感谢吕百达教授、郑启光教授以及刘江龙教授对作者的热情支持,使该书的出版获得国家科学技术学术著作出版基金的资助;同时,衷心感谢丘军林教授对本书的精心审阅及对本书内容的建议,使许多问题得到较严格的表述和研究.

本书所涉及的数值计算基本上是作者在微机上编程实现的,所进行的实验及实验数据的整理也基本上是作者亲自参加完成的.书中基本内容、公式及计算结果多数取材于作者近几年在国内外发表的论文,谨期望所成之书能最大限度地减少谬误.然而,由于作者的知识及认识水平所限,不当之处在所难免,切望得到读者指正.

李俊昌

2001 年 3 月于昆明理工大学

Preface

The basic subjects concerned with application research of high-power laser are laser transmission, transformation and thermal acting between laser beam and material. I have engaged in the project research of this field since 1985. The author has kept a steady research cooperation with Institute National des Sciences Appliquée (France), Ecole Centrale de Lyon and Ecole Nationale Supérieure des Arts et Méties de Paris. The author was charged with research project of PSA Etudes et Recherches, French Pretty Motor Corporation and guided the Ph. D. students of France and China. At home, the author has finished one after another the projects come from the Excellent Young Teacher Fund of Chinese Education Commission, The National Natural Science Fundation of China and Natural Science Fundation of Yunnan Province. In research work, the author realizes deeply that scalar diffraction theory, heat conduction theory and computer technology play important roles in the region of laser application research. The knowledge on laser as well as thermal acting of laser and material is obtained step by step in using computer to simulate and solve actual problem.

Light is electromagnetism wave. The macroscopic physical process of light propagation is the diffraction of electromagnetism wave in space. Now, the application of laser nearly extends all over each field of economic construction and national defence research. For quantitatively describing the role of laser in application and research, we have to concern with the diffraction calculation of light wave field. However, the diffraction problem, in general, can be shown

only as a multi-integral whose solution is hardly obtained. It is not a simple thing for scientists and technologists who have very much knowledge on scalar diffraction theory to complete diffraction calculation correctly. In recent years, diffraction calculation may be accomplished conveniently due to the fast development of computer technology and popularity application of computer. Based on the physical concept of light propagation and combining the characteristic of numerical calculation, we have done the deep research on the diffraction calculation and reported the main results in the journals. We think that it is very valuable to summarize our calculation methods and the published papers and present them to readers, which can offer convenience for the graduate students of related special field and scientists or technologists. This becomes main reason of writing this book.

The thermal acting between laser and material is influenced by many definite factors. It is very difficult to compute accurately thermal acting between laser and material with analytic calculation. The better simulation on physical process of thermal acting is achieved basically by pure numeric calculation. However, no matter calculate time or cost using complex pure numeric calculation is not borne in the actual application. Moreover, it is not easy to transplant the numeric calculation model designed basically for specific problem into similar research. To simplify research, the laser beam is usually regarded as ideal Gaussian beam with base-transverse-mode or some ideal beam distributions, and the laser-radiated object is considered as a semi-infinite medium whose thermal physical properties parameters are some constants, and then one can educe some expressions easy to calculation. A lot of hypotheses that are far from actual conditions have been taken in simplifying research so that these research results can not be usually directly served for actual applica-

tion. Research on quick but credible calculation method is still a need basic subject for controlling effectively the thermal acting process between laser and material. Under the financial support from The National Natural Science Foundation of China and Natural Science Foundation of Yunnan Province, based on the technique of fast Fourier transformation (FFT) and the theory of semi-analytic calculation, the author has developed a quick calculation method which approaches relatively experiment results. A useful reference for engineering technicians and graduate students may be provided by the author's research. This becomes another important reason of writing this book.

Therefore, the major content of this book focuses on the calculation problems of laser propagation, transformation and thermal acting between laser and material. The title of this book is decided as "Diffraction of Laser and Calculation on Thermal Acting".

Since the classical electromagnetic field theory is foundation of scalar diffraction theory, in order to make things convenient for students who did not major in optics, an essential introduction to the classical electromagnetic field theory and the scalar diffraction theory is given in the Chapter 1 and Chapter 2. As known to all, the classical electromagnetic field theory and the scalar diffraction theory were formed more than 100 years ago. However, untill the appearance of laser and computer, has the scalar diffraction theory gobtained a great development in application research in recent decades. Not only becomes it a important theory foundation of modern photo-communication and optical information processing, but, according to classical Fresnel diffraction integral, a lot of diffraction formulas have presented which focus on some specific problems. The Collins formula is a representation of them. For mirroring the new progress of diffraction calculation in this book, when writing these two chapters, the

author referred mainly some of monographs that have published in recent years. They are: *Engineering Optics*, writed by Mr. Yu daoying (Tianjin University) and Mr. Tan hengyin (Zhejiang University), *Propagation and Cortrol of High-Power Laser*, writed by Mr. Lü Baida (Sichuan University) and *Optique*, writed by Marie May and Anne-Marie Cazabat (published in France, 1996).

The 3rd, 4th and 5th chapters have summarized various methods of calculating diffraction integral in space range and frequency range, and introduced the space trace method on calculating diffraction field in the case of light wave passing through off-axis optical system by equivalent by-axis optical system. Calculating diffraction of light correctly is a most important content in the research of optic information processing. In these three chapters, to confirm the feasibility of each method, the author gave several actual examples of comparing theory calculation with experiment measurement. According to the calculation formulas in this book, readers who have basic knowledge on science calculation and computer program should get the same results and may solve the problems relating to application research by writing programs.

Since diffraction calculation is concerned with the definition and measure of laser beam parameters, in Chapter 6, the definitions on beam parameters of Gaussian beam and general beam are discussed using diffraction theory and two detection methods on power density distribution of high-power laser are introduced briefly. In Chapter 7, some typical beam transforming systems of laser process and heat treatment are expounded. The diffraction calculation method that was introduced in this book has comprehensive application in chapter 7. Readers can find out clearly that scalar diffraction theory can calculate accurately space change process of light wave field when coherent light passing through the optical system. For the readers en-

gaging in research on interaction of laser and material, they can form more direct concept on beam intensity distribution that reaches actually material surface. The optical systems we discussed mainly met the needs of process and heat treatment of industrial laser. In the application research of high technology, however, the research on well-distributed of high-power laser follows the same principle and theory. We believe that the discussion in this book is also beneficial for researchers who engaging in the application research of high-power laser.

In Chapter 8, we introduced the semi-analytic calculation and FFT calculation method on thermal acting between laser and material. In this chapter, we did not assume the laser beam has ideal distribution and not regard the laser-radiated object as a semi-infinite medium. Starting from the analytic solution of heat conduction equation of infinite medium with constant thermal physical properties parameters, we dealt with boundary problem by introducing various "image heat source" and discussed some quick calculation methods that are closer to actual application and got the experimental support. We listed more detail calculation formulas and theoretical proof for each kind of calculation method, and gave the comparison of theoretical calculation and actual measurement.

The Chapter 9 includes brief induction of pure numerical value calculation method and research on some more complex physical processes between laser and material. In international cooperation, Mr. Chen Qinghua and Mr. Fu Yunchang (Kunming University of Science and Technology) performed study successfully in this field by using abroad experiment condition. From this chapter written by them, readers may understand the basic method and partial calculating examples for solving thermal acting problem by method of finite difference and finite element, and know a lot of physical models and

mathematical representatives on more complex thermal acting between laser and material. The more elaborate calculation formula has been given for each calculating example. It is helpful very much for graduate students and researches. In the end, the basic knowledge of Fourier transformation and several special functions which concerned with in theoretical calculation of this book were introduced briefly in the appendix.

The author thanks Prof. Lü Baida, Prof. Zheng Qiguang as well as Prof. Liu Jianglong, who gave the enthusiasm support for author and made the publication of this book obtain the financial aid of The National Science and Technology Academic Works Publication Fund. At the same time, author thanks Prof. Qiu Junlin, who carefully read the book and gave advice for content and structure of this book so as to a lot of problems got more strictly statement and research.

The numerical value calculations involved in this book were performed basically in computer by author's programming, and the experiments and management on experimental data were performed under author's attendance. The greater parts of basic contents and formula and calculation results in this book were selected from author's papers that published at home and overseas in recent years so as to this published book can furthest reduce falsehood. Because of limitation in knowledge and knowing level, however, the author looks forward to getting reader's comment on unsuitable spots.

Li Junchang

Kunming University of Science and Technology, March, 2001

目　录