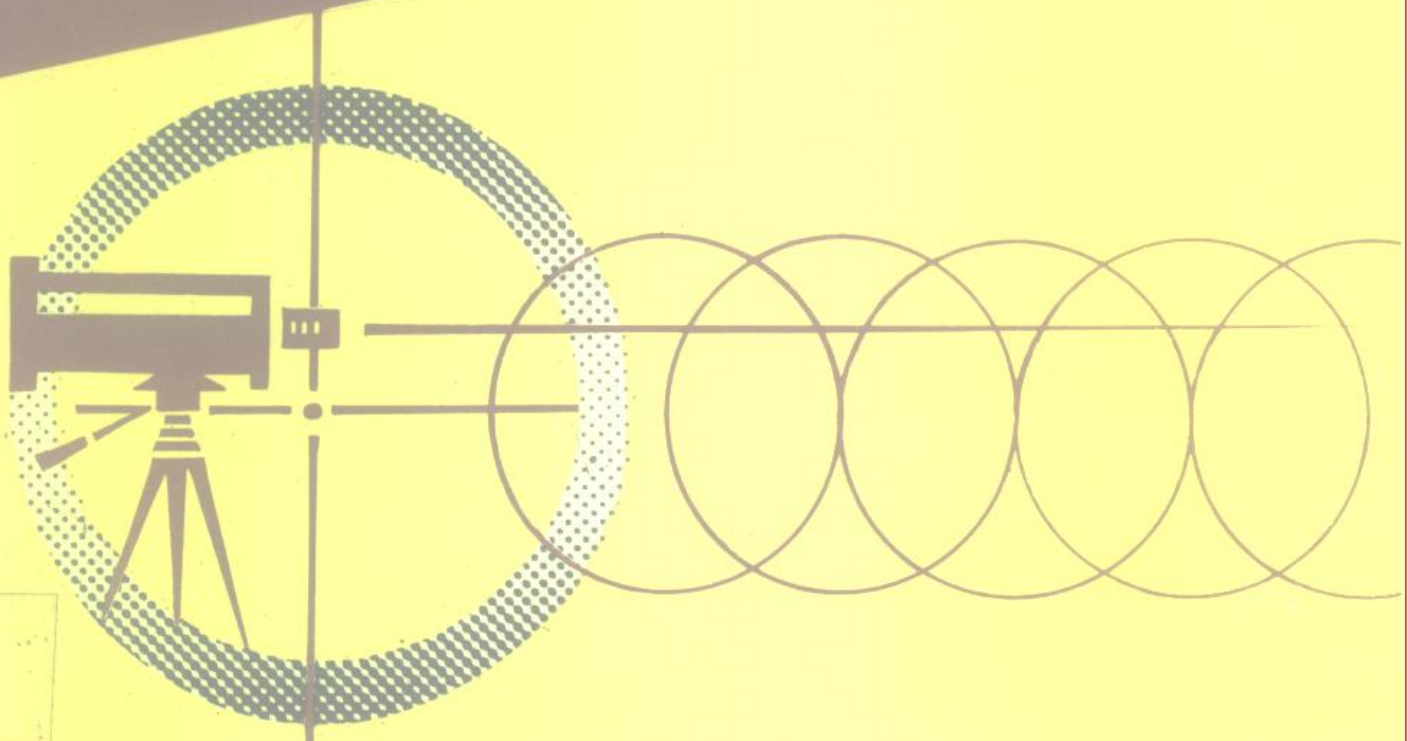
LASER OPTICS

Laser Beam Propagation and Beam Quality Control

激光光学

激光束的传输变换和光束质量控制

● 吕百达 著



四川大学出版社

激光光学·激光束的传输变换和光束质量控制（第二版）
四川大学出版社

LASER OPTICS

Laser Beam Propagation and Beam Quality Control

激光光学

激光束的传输变换和光束质量控制

第二版

吕百达 著

四川大学出版社
1992年·成都

（川）新登字014号

责任编辑：杨守智
封面设计：冯先洁
技术设计：杨守智

激 光 光 学

——激光束的传输变换和光束质量控制

吕百达 著

四川大学出版社出版发行（四川大学校内）
四川省新华书店经销 成都市郫县犀浦印刷厂印刷
开本787×1092 1/16 25.5印张 580千字
1992年12月第二版 1992年12月第一次印刷
印数 3001—6000册

ISBN7-5614-0565-0/O·74 定价：14.00元

内 容 提 要

本书研究激光光束通过光学系统、各种介质的传输变换以及光腔的物理和技术问题。修改后的第二版比之第一版在篇幅和内容上都有大的增加。全书共十章，可分为两大部份。第一部份包括第1－3章和第6、7章，阐述激光光学的基本理论和分析方法。第二部份，即其余五章讨论激光光学专门问题和这一领域某些新的进展。本书内容丰富、取材新颖，反映了国内外最新研究成果和作者的独立见解，每章末附有习题和参考文献供进一步学习选用。

本书可作为高等院校光学、光电子技术有关专业的高年级本科生和研究生的教材，也可供在相应领域内工作的科技人员作参考。

序

激光光学是研究激光束在空间传输变换的一门分支学科。在激光发明以前，研究光束通过光学系统的传输特性多以匀振幅光束为对象，而由腔模决定的激光束为非匀振幅光束，从而带来激光科学工作者感兴趣的一些新的传输特性，高斯光束的传输就是一个典型的例子。

作者娴熟地利用矩阵光学方法，并使之与光学衍射理论相结合，既简洁又清楚地描述了激光束的传输变换，特别是对谐振腔内光束特性的分析，更为系统、完整。

作者吕百达教授长期从事光束传输的研究，有深厚的基础。本书是他十多年来从事激光光学科研和教学工作成果的总结。在书中，由浅入深组织的材料相信对入门读者会是特别有用的。我认为，这是一本激光光学方面的好书，特此推荐再版。

邓锡铭　教授

1992年5月20日于上海光机所

Foreword

"Laser Optics" is a branch subject, dealing with laser beam propagation and transformation in space. Before the invention of the laser, the attention to the studies of the characteristics of beam propagation through optical systems was mainly focused on the beams with uniform amplitude, whereas the laser beams determined by resonator modes are those with non-uniform amplitude, bringing about some novel propagation characteristics, which are of interest to the laser scientists. And the Gaussian beam propagation is one of the typical examples.

By skillfully using matrix optical methods and combining them with the diffraction theory in optics, the author of this book gives a comprehensive and clear-cut description of the laser beam propagation and transformation. Especially, the analysis of the beam characteristics in resonators is more systematic and complete in this book.

The author, Prof. Baida Lü, has devoted himself to studying beam propagation and transformation for a long time and mastered the fundamentals in this field deeply. This book is a summary of the results of his research and teaching in laser optics in more than ten years. Moreover, the step-by-step—organized material is believed to be useful for the beginners in this field. Hereby I am pleased to recommend this worthwhile book to the republication.

Shanghai Institute of Optics
and Fine Mechanics, Academia Sinica
May 20, 1992

Prof. Ximing Deng

第二版前言

自1983年起，作者在四川大学对光学专业本科生和硕士研究生讲授《激光光学》和相关课程，1986年曾将所用讲义整理成《激光光学》一书由四川大学出版社出版，并在国内一些高等院校和研究所试用。现根据读者意见并为反映激光光学近年来的进展，对原书作了大的修改和增加内容后再版。

激光光学研究激光光束通过光学系统、各种介质（诸如均匀和非均匀介质、各向同性和各向异性介质、非线性介质等）的传输变换以及光腔物理和技术问题，以实现光束质量控制之目的。自1960年激光问世以来，受到中外学者的广泛重视，激光光束的传输特性、光腔物理和技术问题相关的研究工作一直很活跃，进展很快，涉及内容非常丰富，文献浩如烟海，应用目的也十分明确。修改后的《激光光学》共分为两大部份，其中第一部份包括第1—3章和第6、7章，即激光光学概论、光学中的矩阵方法、高斯光束、简单两镜光学谐振腔和光腔的衍射积分理论，为基础性内容，阐述激光光学的基本理论和分析方法。第二部份，即其余五章讨论激光光学专门问题和这一领域某些新的进展，例如高斯—谢尔模型光束、无衍射贝塞尔光束、广义时—空域衍射理论、多元件光学谐振腔、含热透镜腔的动态工作特性、相位共轭腔、非轴对称腔、光腔的失调特性和激光器的光泵浦热效应等，读者使用本书作教材时，可根据不同目的进行选取。参考文献、习题和有关的注释附于每章之末。

在修改本书时，参阅了作者历届教学所用讲稿和大量的中外文献。选材时力求较多地反映我国激光工作者在这一领域的研究成果。学习全书时特别值得推荐的专著是：

1. R. K. Luneberg, "Mathematical Theory of Optics", University California Press, Berkely, Calif., 1964.

2. A.E. Siegman, "Lasers", University Science Books Mill Valley, California, 1986.

3. H.Weber, "Optische Resonatoren", Festkorper-Laser Institut Berlin GmbH, 5.Auflage, 1988.

4. D.R.Hall and P.E.Jackson, "The Physics and Technology of Laser Resonators", Adam Hilger, Bristol and New York, 1989.

对过去十多年中在作者所在研究室工作过的同事和学生在完成本书时给予的友好帮助作者表示非常感谢。在修改本书过程中，作者曾得到H.Weber、邓锡铭、梅遂生、范滇元、周寿桓、匡一中、王清月、魏光辉、王绍民和卢亚雄等教授许多十分有益的帮助和鼓励。特别是邓锡铭教授热心为第二版作序，H.Weber教授寄来了对本书修改很有参考价值的柏林固体激光研究所的工作报告、学士和博士论文，与范滇元教授就涉及光束传输和在强激光技术中的应用所进行的多次富有启发性的讨论使作者受益匪浅，特此

一并致以深切的谢意！

限于作者学识水平，错误和不足之处难免，恳请阅者批评指正，以期再版时得以改进。

吕百达于成都

一九九二年五月

Preface to the Second Edition

Since 1983, the author has been giving lectures on "Laser Optics" and related courses to the undergraduate and graduate students majoring in Optics at Sichuan University. In 1986, the book "Laser Optics", which was compiled and organized on my lecture manuscripts, was published by Sichuan University Press and used in several universities and institutes in China. In preparing the republication, some revising and enlarging work has been done based on the first edition, according to reader's comments, so as to include the recent advances in laser optics these years.

Laser optics deals with laser beam propagation and transformation through optical systems, in various media, such as homogeneous/inhomogeneous, isotropic/anisotropic and nonlinear ones, as well as resonator physics and technology, so as to realize beam quality control. Since the first laser in het world was discovered in 1960, the propagation properties of the optical beams generated by lasers, and the physics and technology of optical resonators have been paid wide attention to, the relevant research work has developed vigorously. There are quite extensive subjects, quite a lot papers to read, and the application aims are quite explicit. The revised edition is composed of two parts, of which the first part, containing chapters 1-3 and 6-7, i.e., introduction to laser optics, matrix methods in optics, Gaussian beams, simple two-mirror resonators and diffraction integral theory of optical resonators, is the basic one that provides elementary theories and useful analytical tools of laser optics. The second part, i.e., the rest five chapters, is concerned with some specific topics and advances in laser optics, e. g., Gaussian Schell-model beams, diffraction-free Bessel beams, generalized diffraction theory in the time-space domains, multielement resonators, dynamical properties of resonators with an internal thermal lens, phase-conjugate resonator, axis-asymmetric resonator, misalignment characteristics of optical resonators, and thermal effects in optically pumped lasers etc., from which readers can choose what they need according to their own purposes, when "Laser Optics" is used as a textbook. References, problems and related illustrations are included at the end of each chapter.

My lecture manuscripts used each year and a great number of papers

published both in China and abroad are referred when I revise this book, intending to reflect the research results obtained by the Chinese laser scientists and engineers in this field in more details. While studying the whole book, the following monographs and books are espécially worth recommending:

1. R. K. Luneberg, "Mathematical Theory of Optics", University California Press, Berkeley, Calif., 1964.

2. A. E. Siegman, "Lasers", University Science Books Mill Valley, California, 1986.

3. H. Weber, "Optische Resonatoren", Festkörper-Laser-Institut Berlin GmbH, 5. Auflage, 1988.

4. D. R. Hall and P. È. Jackson, "The Physics and Technology of Laser Resonators", Adam Hilger, Bristol and New York, 1989.

I wish to acknowledge my colleagues and students working in our institute for their kind help during the past ten years while this book was being written. And I am indebted to the following professors whose suggestions and encouragements have certainly contributed toward improving the book in a number of ways: Profs. H. Weber, Ximing Deng, Suisheng Mei, Dianyuan Fan, Shouhuan Zhou, Yizhong Kuang, Qingyue Wang Guanghui Wei, Shaomin Wang, and Yiaxong Lu. I am especially thankful to Prof. Ximing Deng, who wrote the foreword for the second edition and to Prof. Dr. H. Weber, who kindly sent me the research reports, diploma theses and dissertations of Festkörper-Laser-Institut Berlin, which were quite helpful while revising the book. My great thanks must go to Prof. Dianyuan Fan for our fruitful discussions concerning the beam transformation and applications to high power laser technology.

On account of the limitation of the author's knowledge, there might be some shortcomings and mistakes. Any criticism and corrections from the readers are highly welcomed in order that the book be improved when republished again in the future.

Chengdu May, 1992

Baida Lü

第一版 前 言

激光光学研究激光通过光学系统、各种介质和在光学谐振腔内的传输和变换的规律。前者包括激光通过光学成像系统（透镜、望远镜系统、透镜序列等）、非均匀介质、各向异性介质和非线性介质等的传播问题，后者则构成光学谐振腔的研究内容。系统地掌握这些知识，对激光工作者来讲都是必要的。

全书共十章，可分为二大部分。第一部分包括前五章基础内容，介绍激光光学中的基本概念，其中矩阵光学、高斯光束和衍射积分方程理论为重点。为了便于自学，这一部分在写法上尽可能给出了数学推导的主要步骤并注意对使用方法和所得结果从物理上加以说明。第二部分包括后五章，讨论激光光学专门问题，如多元件光学谐振腔、环形腔、光腔的失调特性、光泵浦热效应和与光腔设计有关的问题等。这一部分在写法上注意了突出重点，着重说明如何应用基本方法来解决实际问题。

本书力求从实用角度出发，用比较易于理解的方式来阐述理论，重点放在理论的应用上，较严格的理论表述可以在章末所列参考文献中找到。虽然激光物理和激光技术的书籍和文献经过二十多年积累已相当丰富，但在激光光学、光学谐振腔方面的专著却很少。在本书编写过程中广泛参考了国内外有关文献和资料，内容的取舍上则主要根据编者的需要。在全书的系统性、讲述方法及对一些问题的研究方法和诠释上反映了编者个人的见解。对于所采用的文献，则经编者复算和整理，与原文不全相同。每章末附有习题供练习之用，对正文中一些问题的进一步讨论也放在习题中。遗憾的是，受篇幅所限和因安排上的问题，激光在光纤和波导管中的传播、大气光学等内容都没有包括进去，所幸在这些方面已有一些优秀著作可供参考。具有高等数学、原子物理、数理方程、光学、电动力学和激光基本知识的读者，在阅读本书过程中不会遇到原则性的困难。

本书是编者在四川大学物理系光学专业和成都地区激光讲习班上使用的讲义基础上加以修改、增删而成的。无论是编者在西德凯泽斯劳藤（Kaiserslautern）大学从事光学谐振腔专题研究期间或是在编写本书过程中都得到了 H.Weber 教授十分友好和热情的帮助，为了深入讨论一些问题，常常占用了他不少休息时间。编者还与 W.Demtröder 教授进行了多次十分有益的讨论，书中使用了Kaiserslautern 大学两位教授领导研究室有关的学术报告、学士论文和博士论文中的一些研究结果，为此谨向 H.Weber 教授和 W.Demtröder教授表示衷心的感谢。四川大学激光物理与激光化学研究室主任匡一中教授审阅了原稿，并提出宝贵意见，北京工业学院魏光辉先生、杭州大学王绍民先生提供了一些有价值的学术论文，四川大学出版社为本书早日问世作了大量工作，特此一并致谢。

虽然在试用过程中对本书曾加以修改，但这是一个包含内容十分丰富并在发展中的

研究领域，为编者学识水平所限，谬误之处在所难免，诚挚地期望读者批评指正，不胜感谢！

吕百达谨识于四川大学

一九八五年十二月

Preface to the First Edition

"Laser Optics" deals with laser beam propagation and transformation through optical systems, in various media and inside optical resonators. The former includes the laser beam propagation through optical imaging systems (lens, telescopic system, lens sequences etc.), inhomogeneous medium, anisotropic medium and nonlinear medium, while the latter forms the contents of optical resonator theory. It is necessary for laser scientists and engineers to grasp these materials systematically.

The book is divided into two parts, containing ten chapters. Part one, including chapters 1-5, is the basic part that introduces the basic concepts of laser optics, of which three chapters are the key points, i.e., fundamentals of matrix optics, Gaussian beams, and diffraction integral theory. In order to facilitate self-study, the main procedures of mathematical reasoning are given in this part. The methods used and the results obtained are explained physically. Part two includes the last five chapters, i. e., chapters 6-10, dealing with some special topics in laser optics, for example, multielement resonators, ring resonator, misaligned characteristics of optical resonators, thermal effects in optically pumped lasers and the problems concerning resonator design. What is stressed in this part is how to solve practical problems by means of these basic methods.

For practical purposes, this book focuses on the applications of the theories, and methods which are easy to understand are used to elucidate the theories, while more strict theoretical treatments can be found in the reference literatures listed at the end of each chapter. Although the books and literatures on laser physics and laser technologies have accumulated to a certain degree all these past twenty years, the monographs on laser optics and optical resonators are quite limited. The related literatures and materials both in China and abroad are widely referred to and elaborately selected according to the author's need while organizing the materials. The author's personal views are also reflected in the book. Some reference materials are recalculated and organized by the author and are not exactly the same as the original ones. Problems and exercises are attached to the end of each chapter, and further discussions of some special topics in the

text are also put in the problems. It is much to be regretted that the contents concerning the laser beam transformation and propagation in optical fibres, waveguides and atmosphere are not included, limited by the length of the book. Fortunately, there are some excellent monographs in these areas to be referred to. Readers with the knowledge of advanced mathematics, atomic physics, methods of mathematical physics, optics, electrodynamics, and principles of lasers will not encounter any essential difficulty when studying this book.

This book is corrected and revised based on the lecture manuscripts I wrote for the class of undergraduate and graduate students majoring in Optics of the Physics Department of Sichuan University and the laser seminars in Chengdu. I am very indebted to Prof. Dr. H. Weber for much friendly and enthusiastic help while both going on research work on optical resonators at Kaiserslautern University of West Germany during 1980-1982 and writing this book. Besides, several fruitful discussions with Prof. Dr. W. Demtröder are also quite helpful. Some results in the research reports, diploma theses and dissertations of the research groups leaded by these two professors of Kaiserslautern University are used in this book. Here I wish to express my heartfelt thanks to them. Prof. Yizhong Kuang, Director of the Institute of Laser Physics and Laser Chemistry of Sichuan University, examined the manuscripts and gave some useful comments. Several valuable papers are provided by Mr. Guanghui Wei of Beijing Institute of Technology and Mr. Shaomin Wang of Hangzhou University. A lot of efforts are made by Sichuan University Press to make sure that this book be published as early as possible. I am especially thankful to all of them.

Although this book has been revised while being on trial, shortcomings and mistakes are still inevitable since this is a research field which covers wide areas and is still in development. Corrections of errors and misprints from readers are highly welcomed and indebted to.

Sichuan University Dec., 1985

Baida Lü

本书使用主要符号一览表

A、B、C、D	变换矩阵 $\begin{bmatrix} A & B \\ C & D \end{bmatrix}$ 诸元素
a、b、c、d	变换矩阵 $\begin{bmatrix} a & b \\ c & d \end{bmatrix}$ 诸元素
B	磁感应强度
C	光速/比热
D	失调灵敏度参量/光焦度
E	电场强度/杨氏模量/能量/单位矩阵 $\begin{bmatrix} 1 & 0 \\ 0 & 1 \end{bmatrix}$
F	菲涅尔数/透镜焦距
f	透镜焦距/频率
G	G参数/光腔的特征参数
g	g参数
g'、g''	g'参数，g''参数
g^*	g^*参数
g'^*、g''^*	g'^*参数，g''^*参数
g_0	小信号增益系数
H	磁场强度
h_1、h_2	厚透镜主面与顶点间距离（主距）
I	光强/单位矩阵 $\begin{pmatrix} 1 & 0 & 0 & 0 \\ 0 & 1 & 0 & 0 \\ 0 & 0 & 1 & 0 \\ 0 & 0 & 0 & 1 \end{pmatrix}$
J	电流强度
k	波数
L	腔长
l	激光介质长度/距离
M	矩阵/不稳腔往返一周放大率/磁化强度
M_1、M_2、M_3	M_1角放大率，M_2横向放大率，M_3轴向放大率
M^{-1}	M的逆矩阵
M^T	M的转置矩阵
M^+	M的转置共轭矩阵
$\overleftarrow{M}$	M的反向变换矩阵
M^2	M^2因子

m	不稳腔的单程放大率
m, n	横模序数（矩形域）
N	光子密度
P	功率
p, l	横模序数（园形域）
Q	腔的品质因数（Q值）
Q^{-1}	高斯光束复波前矩阵
q	高斯光束q参数/纵模序数
R	反射率/高斯光束等相面曲率半径/球面波曲率半径
r	半径/径向坐标
s	匹配因子/稳定性因子
T	透射率/温度
U	能量
u	物距
V	损耗因子
v	像距
W_m, W_n, W_{pl}	高阶高斯光束光斑半径
w_1, w_2	腔反射镜处基模高斯光束光斑半径
w_0, w_i, w_{0i}	基模高斯光束腰斑半径
Z_0, Z_{0i}	基模高斯光束瑞利尺寸
Z_m, Z_n	高阶高斯光束瑞利尺寸
α	损耗系数/吸收系数/线胀系数/角度/α矩阵
β	β值/角度/β矩阵
γ	本征值/γ矩阵
δ	功率损耗
σ	电导率/高斯光阑宽度/相关长度
χ	线性极化率
τ_R	光子寿命
ρ	腔反射镜曲率半径/密度/距离
$\tilde{\eta}$	介质折射率
η	介质复折射率
$\mathscr{E}$	电场强度复表示
ε_0	真空中的介电常数
ε	介电常数
λ	波长
μ_0	真空中的磁导率
μ	磁导率/复相干度
ϕ	相移/直径

φ	相移/角度
ν	频率/泊松比
$\Delta\nu_q$	纵模间距
$\Delta\nu_c$	无源腔线宽
ω	园频率
θ_0, θ_{0i}	基模高斯光束远场发散角
θ_m, θ_n, θ_{pl}	高阶高斯光束远场发散角
Γ	不稳腔输出耦合率/传输常数
Δ	望远镜离焦量