ORTHOGONAL POLARIZATION in LASERS

Physical Phenomena and Engineering Applications

激光器的正交偏振

物理效应和工程应用

Shulian Zhang / [德] Wolfgang Holzapfel

清华大学出版社

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北京

内 容 简 介

这是一本全面介绍激光器正交偏振的专著，有 4 个部分共 18 章。第 1 部分包括 3 章，介绍激光器的基本知识，包括激光器的基本物理效应，可以产生正交偏振光的激光器类型，激光和正交偏振光束的黑盒子理论。第 2 部分包括 3 章，介绍各种正交偏振激光器，包括塞曼双频激光器、两频和四频环形激光器、双折射双频激光器等，以及各向异性激光腔的矩阵理论。第 3 部分包含 3 章，讨论激光器内的正交偏振光的形成和物理行为，腔调谐（长度改变）揭示的物理现象，正交偏振光回馈大量物理效应，正交偏振激光器的半经典理论。第 4 部分包括 9 章，介绍激光正交偏振效应的新应用，例如高分辨率位移传感，光学元件相位延迟的精密测量，精密、大动态范围的力和压力测量，角度测量及同时测量磁场和转角的四频环形激光器。

这本专著提供了系统的知识，适合科学家、工程师、教授以及大学本科生和研究生参考。

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To Shuyun
(S.Z.)

To Gudi
(W.H.)

Foreword

by Zhou Bingkun

With good grace I have followed the request to contribute a foreword for this monograph written by a Chinese–German author team. One author of this monograph, namely Shulian Zhang, has worked first as a young university lecturer with me since 1970. I know his academic career well and I am familiar with the content in this monograph. I am therefore glad to write a foreword for this book.

Professor Zhang had discussed with me his basic idea of orthogonal polarization in the early beginning of his research. His initial aim was to break through the bottleneck of Zeeman dual-frequency lasers, which outputted a less than 3 MHz frequency difference. The Zeeman dual-frequency laser has been applied as a unique light source of interferometers for several decades, which has pushed manufacturing industry greatly, including IC equipment, machine tools, automobiles, etc. The upper limit of the frequency difference less than 3 MHz comes from the physical principle of Zeeman lasers and limits the measurement speed of interferometers to 1 m/s, which limits the production efficiency of IC equipment and machine tools. How can the frequency difference in a laser be enlarged? The idea to put a quartz crystal into the standing-wave laser cavity to gain a frequency difference larger than 40 MHz had succeeded in Zhang's laboratory. That is the birefringence dual-frequency laser. In this laser the quartz crystal plate is used as the element of splitting one mode frequency into two frequencies and tuning their frequency difference. This was the beginning when Professor Zhang started to study systematically the laser frequency splitting and orthogonal polarization in lasers at Tsinghua University.

Zhang's research in the following years yielded not only development of novel birefringence Zeeman lasers with zero to hundreds of MHz frequency splitting but his team has also discovered dozens of laser phenomena and invented several kinds of instruments, which are reported in many peer-reviewed papers. At the same time a number of researchers worldwide have turned to the investigation of orthogonal polarization in lasers, broadened the laser academic space, and built a new researching domain. Meanwhile, this domain has become a new part of laser fundamentals.

Professor W. Holzapfel, the distinguished co-author of this book, is well known in the scientific community for his significant contributions in measurement science and applied optics. His research team at Kassel University, Germany, have also studied systematically orthogonal polarization phenomena in He–Ne lasers and Nd:YAG lasers since the middle of the 1980s. Research was focused on precise force to frequency conversion by photoelastic lasers. The team demonstrated first of all the enormous force measurement capability of

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photoelastic Nd:YAG lasers. Furthermore, the team verified very precise force measurements by photoelastic laser crystals in the time/frequency domain. Holzapfel demonstrated successfully that orthogonally polarized lasers perform extreme broadband vibration detection over many decades.

Besides healthy scientific competition the same interest joins the Chinese and German team together to cooperate successfully for a long time since 1995. Chinese and German scientists share research ideas, results, and together have also written this book. The contents of this book are from a large number of articles and patents published by researchers in France, Germany, USA, UK, Japan, Switzerland, etc., many from S. Zhang and W. Holzapfel. I think some of the reported inventions and findings would be typical samples in laser technology, and bring extensive influence on laser education to students. The monograph has much fresh content, deep theory, and experiments. The laser is often used only as the light source in many traditional laser applications, but here, in this book, the laser itself becomes the sensor, which can be used in the measurement of many physical quantities, such as optical phase retardation inside optical elements, force and pressure, displacement, vibration, angle and magnetic field, etc.

I believe the publication of this book will bring more attention to laser polarization and orthogonally polarized laser. Its theoretical analysis and experimental phenomena can deepen the understanding of general laser theory and accelerate applications of orthogonal polarization, especially in precision measurement. The book will benefit undergraduate students and graduate students significantly and help scientists and engineers to solve their problems. The publication of this monograph is an important and pleasing event for both fields of laser technology and precision measurement.

Zhou Bingkun
Professor of Tsinghua University
Academician of Chinese Academy of Sciences
President of the Optical Society of China
Beijing, July 2012

Foreword

by Konrad Herrmann

This monograph is to my knowledge the first English book covering the topic "orthogonal laser polarization". It deals with specific physical phenomena that may appear in lasers, like

- Laser frequency splitting due to intracavity polarization effects induced by birefringence and optical activity in lasers
- Intensity versus polarization phenomena appearing during cavity tuning of anisotropic lasers
- Optical feedback and laser self-mixing effects due to coupling of orthogonally polarized lasers with cavities.

The observable polarization-dependent phenomena in lasers are really abundant and can appear in different technologies, for instance in Nd:YAG microchip lasers and semiconductor and He–Ne lasers. It is well known for practicing optical engineers that any nonbirefringent material can lose its optical isotropy and can have birefringence, which is often observed in optical components like lenses, prisms, optical fibers, and laser rods, as well as in reflective films and antireflective films on cavity mirrors or windows. This is due to unwanted stresses induced by the component housing and also by residual stresses caused by the fabrication process, for instance due to heat treating. Usually, polarization-dependent phenomena in optical systems and components are mostly evaluated as parasitic and should be eliminated as far as possible.

Contrary to these mainstream evaluations the authors of the book demonstrate that there is a surprising high potential in engineering and application of orthogonally polarized lasers. This conclusion is based on ample experimental data, which they gained with different test equipments and arrangements. The experimental results are explained by application of the Jones matrix theory and Lamb's theory. There is no doubt that polarization-dependent phenomena in lasers can be utilized for very precise, high-resolution measurement and sensing.

A large number of application examples are introduced in the monograph, including optical phase retardation measurement of optical elements, pressure and force sensing, and furthermore measurement of displacement, vibration, angle, and magnetic field, etc. The polarization-dependent laser sensors have some unique advantages due to new principles. For example, laser internal measurements of wave plate phase retardation has vanishing systematic errors, and can be performed with the highest accuracy. The laser force transducer allows combined measurements of static and high frequency dynamic forces up to high frequencies by a single microchip Nd:YAG laser. The measured forces cover the range from well below 10^{-7} N up to more than 10 N, that is at least nine decades of the input force. The microchip Nd:YAG laser feedback interferometer is a fully noncontact interferometer and can measure the displacement of machinery parts and liquid surfaces with 1 nm resolution.

In the context of this book the authors have collected the worldwide achievements of scientists and engineers in past decades. Also by this accumulation of knowledge, which is outside the current main streams of optical measurements, this book has proven its academic worth.

The book will stimulate scientists and engineers in research and development. To the researcher it provides a state of the art to manifold polarization effects in lasers and offers new ways in high precision measurement. Practicing engineers get valuable hints for the design and application of novel laser-based sensing instruments and optical components. The book takes a certain center position between a handbook and textbook, and can therefore also be of benefit to upper level undergraduate and postgraduate students, significantly in advanced courses dealing with optics, lasers, and measurement.

May this book find a wide acceptance between researchers, practitioners, and students of laser measurements!

Dr. Konrad Herrmann
Physikalisch-Technische Bundesanstalt (PTB)
Braunschweig, FRG
July 2012

Preface

This book deals with polarization phenomena in lasers and in particular with lasers emitting radiation in two linear polarizations states, both exactly orthogonally oriented to each other. Although lasers with these special features have been commercially available for some years (for instance internal mirrored He–Ne laser tubes, diode pumped Nd:YAG micro lasers), and numerous scientific papers report related experiments and applications, there is no summarizing book presentation in the scientific literature at present. Laser users in engineering and science are also commonly not aware of the potential advantages of orthogonally polarized lasers. In this book we will try to explain how these uncommon lasers can generate orthogonal polarizations, what their special features and advantages are, and how practicing scientists and engineers can successfully use orthogonally polarized lasers in design and applications. The state of research in this promising technique is discussed in detail. Although not written in the form of a college textbook due to its comprehensive treatment of the subject, the monograph will be useful to students. It might be used successfully in university/college courses on advanced laser technology, measurement, and optical sensing technologies and can serve as a reference book in thesis generation and research.

Contrary to orthogonally polarized lasers, the common lasers emit radiation in uncontrollable polarization states or are single linearly polarized due to utilizing special polarization elements. In many laser applications in which the power of the beam has magnitudes of primary interest polarization control must not be performed.

On the other hand, managing/controlling the polarization state of light sources has long been the tradition in optical science and engineering, for instance in polarimetry and ellipsometry. Polarization control must be performed in excess in modern optical communication systems as well as in other high-speed data transmission systems because these are generally polarization-sensitive systems and it is vital to control polarization of the applied laser diodes to obtain low bit-error rates. To get a light beam in a defined polarization state, discrete optical elements or integrated structures, polarizers, rotators, wave plates (retarders), Brewster plates, and apertures are applied. In this state of the art of laser polarization control the total beam intensity is mostly the favored magnitude of primary interest. However, scientists and engineers often need today more advanced techniques, which must allow very precise control of oscillating laser modes, that is of their individual polarization state and frequency, as well as control of the total number and power of oscillating modes. These advanced techniques are basic for applications of orthogonally polarized phenomena in lasers and we will discuss them in detail in this book.

We point out firstly that orthogonally polarized phenomena in lasers result from optical anisotropy effects in materials including optical activity and birefringence. Optical activity is inherent in several materials, such as quartz crystals, and are also used in Faraday cells. Some other crystalline materials often stressed in classic textbooks, such as calcite, quartz crystals, KD*P, and KTP, are known to have natural birefringence. Moreover, any applied material called not birefringent (i.e. optical isotropic materials) can have birefringence, such as observed in optical components like lenses, prisms, optical fibers, and laser rods made, for instance, of neodymium-doped yttrium–aluminum–garnet crystals (Nd:YAG) and neodymium-doped glasses (Nd:Glas). The same is true even for carefully manufactured laser reflective films and antireflective films on cavity mirrors or windows. This "induced" birefringence may be caused by remaining internal stresses resulting from the fabrication process or by outer mechanical stress sources. For instance, induced birefringence can very easily be introduced in lasers as long as your fingers gently pinch the laser mirrors. Hence you change the polarization state of the laser as well as inducing laser frequency splitting, which means that each mode frequency is split into two orthogonally polarized frequencies and the frequency difference changes by the force of your fingers applied to the mirror. We will explain in detail these effects in later chapters.

We will further make clear in this book that these orthogonally polarized phenomena in lasers should not be classified hastily as unwanted laser disturbances and parasitic phenomena but, based on these polarization effects very useful and precise measurements of unknown "laser input magnitudes" (measurands) can be carried out. Via specific converter effects (optical feedback, photoelasticity in the laser cavity, etc.) and an appropriate input device the measurand generates typical responses in the laser output beam. The dominant response effect is again the above-mentioned frequency splitting of excited modes, which is often accompanied by polarization state changes. These output responses can be easily detected by state-of-the-art electronics if the laser frequency and mode polarization are under control. Due to their unique intrinsic properties orthogonally polarized lasers can often be applied as virtually compensated measurement instruments, which yield high resolution and digitally pleasant frequency outputs. In some cases, by orthogonally polarized effects in lasers the measurand (for instance force, acceleration) can be detected directly as a vector magnitude, which means that its magnitude and its planar pointing direction are measured simultaneously. These features open up new ways in measurement.

Hence, worldwide, some systematic experiments, mathematical modeling, and testing of potential applications dealing with laser polarization and induced splitting of polarized modes have been carried out in the last few years. Scientists from China, France, Germany, the United States, Britain, Japan, Switzerland and other countries have published numerous papers and patents. We, the authors, hope that our monograph reflects much of the global activities in this field but we feel that we cannot be sure that there will be total completeness in our approach. We apologize therefore to any of our colleges whose publications may not be adequately cited and represented in this monograph. Furthermore, we are also aware that there may remain some bugs and imperfections in our presentation although we have tried constantly to avoid these. Hence, we are always open for any hints and critical comments from our readers.

Both authors of this book have performed long time cooperation in research and lecturing since 1995. This cooperation took place not only due to several guest professorships and research visits of Shulian Zhang to the University of Kassel and of Wolfgang Holzapfel to Tsinghua University, Beijing, but also due to permanent exchange of members, ideas, and experiences between both research teams over the past years. At first Shulian Zhang got the idea and yielded a first draft of a basic monograph dealing with orthogonal polarization effects in lasers. Later Wolfgang Holzapfel followed his friendly invitation to write this book together. By this close cooperation both authors would like to express their mutual valuation. Furthermore, both authors would like to give their respect here to the many coworkers and students who have contributed directly and indirectly to the book.

S. Zhang thanks professors, graduates, and undergraduate students in his own team at the Key State Lab of Precision Measurement Technology and Instruments at Tsinghua University for their great efforts. The team continuously studied orthogonal polarization effects in lasers over many years; that is when older students graduated and moved ahead, younger ones joined the team and continued the research. All team members did their best in cooperation, in acquiring basic material for the book manuscript, and last but not least in translation from Chinese to English. The professors who participated in these permanent studies are: Guofan Jin, Yan Li, Yanmei Han, Kelan Li, Jihua Guo, and Minxian Wu. The postdoctoral or doctoral or master's degree students are (in sequence of graduation date): Junjiang Zhang, Dating Zhou, Xiangdong Hu, Sun Yang, Yanmei Han, Yuye Jin, Mingxing Jiao, Yi Zhang, Jia Li, Wenkai He, Zhibing Deng, Yan Xiao, Juncheng Xu, Yingchun Ding, Ming Ren, Jie Fu, Lu Li, Hui Guo, Fang Xie, Chunning Huang, Jinghua Liu, Aihua Zhang, Wenhua Du, Xiaobin Zong, Xinjian Yang, Yingchao Cui, Ligang Fei, Gang Liu, Zhiguang Xu, Ming Liu, Mingming Wang, Xiaoyan Liu, Xinjun Wan, Yong Xu, Xiang Cheng, Li Zhang, Jinyun Ding, Yidong Tan, Lufei Zhou, Duo Li, Wei Mao, Weixin Liu, Liu Cui, Haohao Li, Yanxiong Niu, Matthias Dilger, Chaohui Hu, Zhou Ren, Cheng Ren, Yinan Zhang, Zhengqi Zhao, Chunxin Xu, Peng Zhang, Shoushen Zhu, Zhaoli Zeng, Song Zhang, Weiping Wang, Shijie Zhao, Jiang Li, Haisha Niu, Yongqin Zhang, Shaohui Zhang, Ling Xu, Hao Chen, and Xiaoli Li. Yuye Jin also wrote the first draft of Chapter 2, checked formulas of the first draft, and did translation work.

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We also thank Professor Zhou Bingkun and Dr. Konrad Herrmann, academician members, who have written forewords for this monograph as well as Professor Gerd Jaeger, Technical University Ilmenau, FRG. Throughout our study they have often provided support to the research teams.

Shulian Zhang
Wolfgang Holzapfel

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Introduction

Light beam polarization is a basic characteristic of laser radiation. This book deals with lasers emitting simultaneously two linear polarization states, both exactly orthogonally oriented to each other and consequently split in beam frequency. Although lasers with this special feature are commercial available since years and numerous scientific papers report related experiments and applications, there is no summarizing book at present. The specific advantages of orthogonally polarized lasers are not commonly aware for potential users in engineering and science.

In this monograph we explain how lasers can generate orthogonal polarizations, what their special features and advantages are and how scientists and engineers can successfully use orthogonal polarization and frequency splitting in lasers. There are 4 parts incorporating 18 chapters overall. Part I includes 3 chapters, which introduce fundamentals of lasers and beam polarizations including basic physical effects inside lasers, lasers applicable for polarization controlled beam generation, and laser polarization black box theory. Part II comprises 3 chapters, which introduce special orthogonal polarized lasers: Zeeman dual-frequency lasers, multi-frequency ring lasers, birefringence dual-frequency lasers, and matrix theory of anisotropic laser cavities. Part III contains 3 chapters discussing physical behavior of orthogonal polarization in lasers, physical phenomena revealed by cavity tuning, optical feedback effects and semi-classical theory in orthogonally polarized lasers. Part IV including 9 chapters is dealing with novel applications of orthogonal polarization in lasers, for instance high resolution displacement sensing, precise force and pressure measurements with broad dynamic range, vehicle rotational sensing and combined magnetometer/rate-gyro sensing by four-frequency ring lasers and last but not least precise measurement of phase retardation and other optical anisotropies in optical samples and systems.

This monograph offers systematic material for scientists and engineers, as well as professors, universities graduate and undergraduate students.

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