**学号：**



**博士/硕士毕业论文**

**×××××偏振特性计算方法研究**

|  |  |  |
| --- | --- | --- |
| **研究生** | **：** | **×××** |
| **名称**  **学科专业**  **类别领域** | **：** | **××××××** |
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**×××××偏振特性计算方法研究**

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**Research on Calculation Method of Polarization Characteristics for XXXXX**

by

**XXX**

Dissertation submitted to

**Changchun University of Science and Technology**

Supervisor

Professor **XXX**

Month, 20xx

# **摘 要**

对于高数值孔径显微镜下的聚焦场、辐射光源的近场、倏逝波、横向磁致导波等三维光场，光线的传播并不满足傍轴传输条件，光线追迹过程中的完全矢量化导致传统的偏振光分析方法不能适用于三维光场。关于三维光场的偏振光追迹理论的研究在国内外都刚刚起步，理论体系还不完善。随着激光器技术的飞速发展和广泛应用，采用相干光源的光学系统在现代光学仪器中占据着越来越重要的地位，关于三维相干光场偏振特性计算方法的研究是完整构建三维光场的偏振光追迹理论的第一步，也是最基础和最亟需解决的问题。本文从琼斯矩阵在三维空间的推广出发，开展了三维相干光场的偏振光追迹方法和三维偏振像差理论这两个方面的相关理论研究，并以研究的三维相干光场的偏振光追迹理论为基础，详细分析了角锥棱镜的偏振特性。

在三维相干光场的偏振光追迹方法的研究方面，首先针对三维相干光场，将琼斯矢量推广到三维空间，研究了三维偏振态的琼斯表示方法。三维偏振态不仅包含了光场矢量的偏振椭圆信息，同时也表征了光场传播的方向特性。然后推导出三维偏振光线追迹中三维琼斯矩阵的数学模型，各光学界面的三维琼斯矩阵不仅取决于光学界面的相关物理特性，还依赖于光线的传播矢量。

其次，给出了基于三维琼斯矩阵的二向衰减系数和位相延迟量的计算方法，并讨论了这两个偏振参量在光学系统中传播的一般规律。得出了三维偏振光线追迹中相邻光学界面局部坐标系之间的相对旋转会同时导致位相延迟量和二向衰减系数的改变这一结论。只有当相邻的两个光学表面的入射面相互平行时，这两个光学界面的二向衰减系数和位相延迟量才可以直接求和。若相邻的两个光学表面的入射面相互垂直，则这两个光学界面的二向衰减系数和位相延迟量分别相互抵消的。最后利用三维位相延迟空间解释了位相延迟的缠绕现象，并进一步推导出位相延迟解缠的数学方法。

在三维偏振像差理论的研究方面，首先介绍了偏振像差的两种传统表示方法，即偏振像差函数和偏振像差函数的二次扩展式，在此基础上分析了这两种方法在三维光场中应用时存在的问题，并基于三维琼斯矩阵将偏振像差函数拓展到三维空间，进一步推导出三维偏振像差函数的数学模型。然后利用该数学模型以一个实际的光学系统为例，详细分析了该光学系统各视场三维偏振像差函数的光瞳分布特性，利用18个相互耦合的光瞳函数（9个实部9个虚部）完整描述了光学系统的三维偏振像差。三维偏振像差函数的光瞳分布与波长、视场、光学薄膜以及光学系统的自身结构密切相关。其次，计算了二向衰减像差和位相延迟像差的光瞳分布，并深入讨论了入射光场偏振态对出瞳处光强分布特性的影响，以及偏振效应对传统波像差和点扩散函数的影响。最后，给出了倾斜像差的定义及计算方法。

在角锥棱镜的偏振特性研究方面，根据研究的三维相干光场的偏振光追迹理论，系统地分析了任意偏振态的光线以任意角度入射时，各种不同角锥棱镜（包括全反射角锥、镀铝和镀银的实心角锥和空心角锥）的偏振特性。并指出镀金属膜的角锥棱镜对光束偏振态的改变比全反射角锥棱镜要小得多，即给角锥棱镜镀金属反射膜，是控制出射光偏振态变化的有效技术手段。

本文研究的内容对解决偏振光学领域的一些前沿问题，如精确掌握和分析三维相干光场偏振态的非均匀分布及其演化规律、研究偏振效应对涡旋光束的深聚焦特性的影响、三维相干光场与光学系统的相互作用机理以及优化设计高性能光学系统等科学问题，都具有重要的理论价值和指导意义。

**关键词：**三维相干光场；偏振光追迹；偏振态；二向衰减；位相延迟；偏振像差；角锥棱镜

# **Abstract**

For three-dimensional (3D) light field including focused light field, near-field of radiation light source, evanescent waves, transverse-magnetic guided waves under the microscope with a high numerical aperture, the transmission of light beam does not meet the paraxial transmission condition. The complete vectorization of the ray tracing process leads to the fact that the traditional polarized ray analysis methods cannot be used for 3D light field. Research on the theory of polarized ray tracing for 3D light field is just beginning at home and abroad, and the relevant theoretical system is not perfect. With the rapid development and widespread applications of laser technology, the optical systems with the coherent light sources play more and more important roles in the modern optical instruments. Research on the calculation method of polarization characteristics for 3D coherent light field is the first step to completely build the theory of polarized ray tracing for 3D light field, and it also becomes the most basic and vital issue to be solved. In this dissertation, the Jones matrix was introduced to the 3D space as the start, and then the polarized ray tracing method for 3D coherent light field and the theory of 3D polarization aberrations were studied, and in the end, the polarization characteristics of corner cube were analyzed in detail based on the studied theory of polarized ray tracing for 3D light field.

In the aspect of the research related to polarized ray tracing method for 3D coherent light field, first of all, Jones vector was generalized into 3D space aiming at 3D coherent light field, and Jones representation methods of 3D polarization states were discussed. 3D polarization states not only contained the information about the polarization ellipse of vectorial light field, but also represented the direction of propagation of the light field. Then the mathematical model of 3D Jones matrix in the process of 3D polarized ray tracing was derived, and 3D Jones matrix in each optical interface depended on the physical characteristics of the optical interface as well as the propagation vector of the ray. Secondly, the calculation methods of diattenuation coefficient and phase retardance were derived based on 3D Jones matrix, and the general rules of diattenuation and retardance propagated in optical system were also discussed. It was concluded that the relative rotation of local coordinate systems of two adjacent surfaces in 3D polarized ray tracing could simultaneously change diattenuation coefficient and phase retardance. Only when the incident plane of two adjacent optical surfaces paralleled to each other, total value of the system was equal to the simple sum of all optical surfaces for both diattenuation coefficient and phase retardance. When the incident planes of two adjacent surfaces were perpendicular to each other, diattenuation coefficients of the two surfaces offset each other, and the same is true for phase retardances. Finally, the phase retardance wrapping phenomenon was elucidated by applying 3D retardance space, and the mathematical method of phase retardance unwrapping was further derived.

In the aspect of the research related to 3D polarization aberrations theory, firstly, two traditional ways of representing polarization aberration, namely polarization aberration function and its second extended form, were introduced, and the existing problems of them when applied in 3D light filed were analyzed. Then polarization aberration function was generalized into 3D space based on 3D Jones matrix, and furthermore, the mathematical model of 3D polarization aberration function was given. A real optical system was used as an example, the distribution features of 3D polarization aberration function in exit pupil for different field of view were analyzed in depth *via* utilizing the mathematical model, and the 3D polarization aberrations of this optical system were completely described by using 18 intercoupling pupil functions (9 real parts and 9 imaginary parts). The distribution features of 3D polarization aberration function in the exit pupil had close relationships with wavelength, field of view, optical thin film, and the structure of optical system. Secondly, the diattenuation aberration and phase retardance aberration were calculated, and the effect of incident polarization state on intensity distribution in exit pupil was detailedly discussed, as well as the influence of polarization effect on traditional wave aberration and point spread function (PSF). Finally, the definition and calculation method of tilt aberration were advanced.

In the aspect of the polarization properties of corner cube, the polarization characteristics of various corner cubes (including total reflection corner cube, Al-coated and Ag-coated solid and hollow corner cubes) with an input beam of arbitrary polarization state and arbitrary tilt angle to the cubes were systematically analyzed by using the polarized ray tracing theory of 3D coherent light field. It was pointed out that the variation of output polarization state of metal-coated corner cube was smaller than that of total reflection corner cube. In a word, it is an effective measure to control the polarization states change of the output beam by coating corner cube with metallic reflection film.

The research contents and new findings in this dissertation have important theoretical value and practical guiding significance to solve the forefront issues in the field of polarization optics, such as the accurate grasp and analysis of the non-uniform distribution of polarization states in 3D coherent light field and its evolution law, the influence of polarization effect on the tight focusing properties of vortex beam, the mechanism research of the interaction of 3D coherent light field with optical system, optimization design for optical system, *etc*.

**Keywords:** three-dimensional coherent light field; polarization ray tracing; polarization state; diattenuation; retardance; polarization aberration; corner cube

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# **第1章 绪 论**

## **1.1 选题背景及研究的目的和意义**

偏振特性是光作为电磁波除了光强、位相、光谱等特性之外的重要属性，主要包含光的偏振态和偏振度两个方面，表征了光的矢量性……例如在处理衍射积分的简单解析形式、平面屏的二维衍射、光在介质上的散射等边界条件问题时，都仅用一个光电场分量代表光扰动而忽略电磁波的矢量性[1]。这种简化在某些场合有助于研究和探讨问题的物理图像，避免复杂的数学细节，从而得出比较整齐、解析的结果，但与此同时也丢失了大量的与光矢量属性相关的信息[2]。

（略）

……

对光场偏振特性的准确掌握是有效利用偏振信息的前提，研究发现很多光学系统都是偏振敏感的，特别是具有高数值孔径、高集成度、非近轴运用等特点的高性能光学系统，在这些系统的性能评估中，必须考虑光的矢量性，因为偏振像差将会影响光学成像质量以及聚焦光斑的能量分布等，这也是利用径向偏振光束能够实现超衍射极限聚焦的原因。需要注意的是，在考虑了光的偏振特性后，光场与光学系统之间的相互作用分为两个方面[3]：

……

## **1.2 XXX的国内外研究现状**

人们对偏振光的研究最早可以追溯到17世纪。哥本哈根大学的丹麦数学家E. Bartholinus最早于1669年发现了光在方解石晶体中的双折射现象。……1821年，法国物理学家A. J. Fresnel和D. F. Arago一起研究了偏振光的干涉，确定了光的横波性；并于1823年发现了光的圆偏振和椭圆偏振现象，用波动光学解释了偏振面的旋转，以及马吕斯的反射光偏振现象和晶体双折射现象，奠定了晶体光学的基础。XXXXXX的关系如表1.1所示。

（略）

表1.1 XXXXXX的关系

|  |  |  |  |  |
| --- | --- | --- | --- | --- |
| 工作波段  (μm) | 中心波长  (μm) | 中心波长对应PIDE  (%) | 用式(2.40)计算设计波长  (μm) | 设计波长对应PIDE  (%) |
| 0.4~0.7 | 0.55 | 91.84 | 0.564 | 92.04 |
| 3~5 | 4 | 93.15 | 4.083 | 93.29 |
| 8~12 | 10 | 95.61 | 10.13 | 95.67 |

镀铝实心角锥棱镜的出射光偏振态分布如图1.1所示。 （略）

Fig.17.(b).tif 4-22(b).tif

(a) (b)

图1.1 镀铝实心角锥棱镜的出射光偏振态分布

(a) TM线偏振光倾斜入射；(b) 右旋圆偏振光倾斜入射

……

## **1.3 论文的主要内容**

（略）

# **第2章 偏振光追迹的基础理论**

本章主要介绍一些偏振光追迹理论的基础知识和关键的物理参量，主要包括几种传统偏振光分析方法的基本理论、以及琼斯矩阵和密勒矩阵之间的内在联系。

## **2.1偏振光分析方法**

……

### **2.1.1 瞬时光场矢量的偏振椭圆**

由平面简谐电磁波的波动公式可以得出沿着Z轴方向传播的瞬时光场的两个横向正交电场分量：

 （2-1）

……

1) ……

(1) ……

其特点如下：

① ……

② ……

③ ……

各参数指标如下：

a) ……

b) ……

### **2.1.2 斯托克斯矢量法**

### **2.1.3 庞加莱球表示法**

……

## **2.2 琼斯矩阵与密勒矩阵的内在关系**

## **2.3 本章小结**

（略）

# **第5章 基于XXXXX偏振特性分析**

……

## **5.1** **角锥棱镜的几何模型**

……

### **5.1.1 全反射角锥棱镜的几何模型**

……

……

## **5.2 全反射角锥棱镜的偏振特性**

……….

## **5.3 镀金属膜的角锥棱镜的偏振特性**

……….

## **5.4本章小结**

……

本章以角锥棱镜为例，简单地阐述了三维相干光场的偏振光追迹理论对现有光学技术的改进所具有的指导意义。

# **第6章 结论与展望**

## **6.1 结论及创新点**

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## **6.2展望**

……

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# **附录A 相关程序代码**

附录A为第四章第4.2.2节中关于USA patent 2604013光学系统的三维偏振像差函数在出瞳处的分布的MATLAB程序代码。

%polarization ray tracing for USA patant 2604013

clc;clear;

syms OPL\_surf1

%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%

m=257;

n=257;

lamd=546;

INR\_611=1.613483;

INR\_720=1.725819;

INR\_734=1.737419;

INR\_697=1.699961;

INR\_523=1.525132;

FOV=0;

FOV=FOV\*pi/180;

entrance\_pupil\_D=1.2;

entrance\_pupil\_P=2.4307;

exit\_pupil\_D=0.4107;

exit\_pupil\_P=-0.3373;

R11=zeros(m,n);R12=zeros(m,n);R13=zeros(m,n);R21=zeros(m,n);R22=zeros(m,n);R23=zeros(m,n);R31=zeros(m,n);R32=zeros(m,n);R33=zeros(m,n); I11=zeros(m,n);I12=zeros(m,n);I13=zeros(m,n);I21=zeros(m,n);I22=zeros(m,n);I23=zeros(m,n);I31=zeros(m,n);

I32=zeros(m,n);I33=zeros(m,n);

position\_exit\_pupil\_x=zeros(m,n); position\_exit\_pupil\_y=zeros(m,n); OPL\_total=zeros(m,n);

%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%

ray\_x=linspace(-0.5\*entrance\_pupil\_D,0.5\*entrance\_pupil\_D,m);

ray\_y=linspace(-0.5\*entrance\_pupil\_D,0.5\*entrance\_pupil\_D,n);

for k=1:n

for j=1:m

……（略）

# **攻读硕士学位期间取得的成果**

1) 发表论文

(1)XXX, XXX, XXX, ……. Polarization properties of a corner-cube retroreflector with three-dimensional polarization ray-tracing calculus. Applied Optics, 2013, 52(19): 4527-4535 (SCI收录, 检索号: 000321289700015)

(2) ……

2) 著作

(1) XXX, 出版集团研究. 北京: 中国书籍出版社, 2001

(2) ……

3) 专利

(1) XXX, XXX, XXX, ……. 一种高速铁路轨道平顺性的检测装置. 国家发明专利. 授权号：ZL201110120209.8，授权公告日：2013.08.14

(2) ……

4) 参加的科研项目

(1) 国家自然科学基金面上项目《XXXXX计算方法的研究》，批准号：11474037；

(2) 国家高技术研究发展计划（863计划）课题《XXXX高光谱偏振成像技术》，批准号：XXXXXXXXX；

(3) 吉林省自然科学基金项目《XXXX偏振光谱成像机理的研究》，批准号：20130101JC032；

5) 获奖情况

(1) 国家教育部《硕士研究生国家奖学金》，证书编号：2013年第03149号；

(2) 中国仪器仪表学会《中国仪器仪表学会奖学金》二等奖，证书编号：2013-46

# **致 谢**

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