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Lei Yan · Bin Yang · Feizhou Zhang ·
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Polarization Remote Sensing Physics

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Lei Yan
Earth and Space Science
Peking University
Beijing, China

Feizhou Zhang
Peking University
Beijing, China

Wei Chen
China University of Mining
and Technology, Beijing
Beijing, China

Bin Yang
College of Electrical
and Information Engineering
Hunan University
Changsha, China

Yun Xiang
Hebei Academy of Meteorological Sciences
Shijiazhuang, China

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Foreword By Huilin Jiang

The polarized signal is an important component of the surface and atmospheric system reflection signals and is an important signal source for retrieving surface and atmospheric information using remote sensing information. However, the current research on optical remote sensing mostly focuses on non-polarized remote sensing, and there are few studies on polarization remote sensing, which neglects an important data source in remote sensing inversion.

In response to this, the author of this book conducted a long-term systematic study from four aspects, including the physical basis of polarization remote sensing, the polarization remote sensing of ground object parameter inversion, the polarization remote sensing of atmospheric parameter inversion, and the application of polarization remote sensing.

This book contains not only a theoretical breakthrough, but a series of practical experiments. Based on the data analysis of more than 300,000 sets of field experiments conducted by the author's research team since 1978, the theoretical system of optical polarization remote sensing is established, and the main material in this book stems from the theoretical achievements and experimental accumulation of the research team led by the first author over the past 40 years.

Polarized remote sensing technology, with its objectivity, stability, and repeatability, should take the leading responsibility in the China Geoscience Research. The book provides a new vision for the practitioners in related fields to solve their own problems by means of polarization remote sensing and can be used as a guide for polarized remote sensing research to understand polarization remote sensing theory.

Huilin Jiang
Changchun University of Science and Technology
Academician of Chinese Academy of Engineering

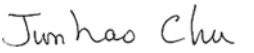
Foreword By Junhao Chu

Polarization is an important part of the surface reflection signal, but optical polarization remote sensing still lacks in-depth research and application. The international astronomical community mainly uses polarization methods for the study of the sun, stars, and planets. Optical polarization is expected to play a role in the remote sensing science.

From the optics point of view, the solar electromagnetic wave is the only carrier that runs through the whole process of remote sensing, including the atmosphere, the surface and the observation instrument. By exploring the polarization parameters from the optics point of view are we able to make the whole remote sensing process have a unified physical dimension and lay the foundation for the integrated automation model construction of remote sensing.

This book mainly analyzes the two geoscience inversion bottlenecks: the intensity of the ground reflection spectrum and the attenuation error effect of the atmospheric window. The author comprehensively summarize the physical principle of polarization remote sensing, and use polarization remote sensing to solve the problem of target detection under the over-bright or over-dark background.

This book is a reference book for practitioners in the field of optical polarization to learn the application of polarized optical technology in the field of remote sensing. It also provides a new technical solution for practitioners in the field of remote sensing. It can be used as a guide for polarization remote sensing scientific research and a teaching material to understand polarization remote sensing theory, techniques and methods.



Junhao Chu
Shanghai Institute of Technical Physics
Chinese Academy of Sciences
Academician of Chinese
Academy of Sciences

Foreword By Jouni Peltoniemi

Polarization is expected to play a role in the burgeoning science of remote sensing, however, the realization of application goals requires the establishment, interpretation, and breakthrough of a sound theoretical basis. So far, there are no books systematically and comprehensively introducing the mechanism, theory, and application of optical polarization remote sensing, either at home or abroad. The publication of this book fills the theoretical and experimental gaps in this cognate area.

In this book, Prof. Yan has contributed to the polarimetric effects of three elements of remote sensing processing-chain, i.e. ground, atmosphere and instruments, as well as the three-element-related integrated modeling, observation methods and instrumentation. He has established a series of polarization inversion models of three-element high-resolution quantitative remote sensing, adding an additional dimension to the domain of resolutions; besides spatial, spectral, radiometric and temporal resolution, also the degree of polarization can now be considered. He has led to new theoretical and experimental results in the areas of representation, capture and analysis of polarized electromagnetic radiation. He has developed the theory and mechanism of a new earth polarization field. The field contains not only the "line", i.e. the sky polarization distribution, but also the "central point", i.e. atmospheric polarization neural point. The polarization field makes a new atmospheric window for ground observation, and reveals information of atmospheric pollution and many other meteorological characteristics.

This monograph is the first in the world to integrate the theory, methodology and applications of polarimetric remote sensing, providing good foundation for polarimetric remote sensing method and instrumentations.

Jouni Peltoniemi
Finnish Geospatial Research
Institute FGI, Research manager
of space geodesy

Preface

Polarization is an important part of the surface reflection signal, but polarization information has not received the attention it deserves in remote sensing. At present, the US NASA has recognized the significance of polarization remote sensing and has developed a new type of polarization sensor; France has already used polarization remote sensing detectors, and the international astronomy community mainly uses polarization methods for the study of the sun, stars, and planets. Polarization remote sensing will inevitably play a huge role in the ascending remote sensing discipline. However, there are no books at home and abroad that systematically introduce the theory and application of polarization remote sensing. Therefore, the author analyzes the current status and trends of polarization remote sensing research at home and abroad and summarizes the research results of his team for more than 20 years since 1988 to complete the full text of this book.

This book introduces five characteristics of polarization remote sensing: multi-angle reflection physical features (Chap. 2), multispectral chemical properties (Chap. 3), roughness and density structure properties (Chap. 4), characteristics of info-background high contrast ratio filter (Chap. 5), and the features of radiative energy transfer (Chap. 6). This book introduces important connotations of atmospheric polarized remote sensing: the nature and physical characteristics of the full-sky polarization pattern (Chap. 7), regional characteristics of atmospheric polarization neutral points and decoupling of ground-atmospheric parameters (Chap. 8), and multi-angle stereoscopic observation chromatography of atmospheric particles under full-sky polarization vector field (Chap. 9). This book introduces new areas in polarization: bionic polarization automatic navigation based on earth's polarization vector field (Chap. 10), polarization remote sensing methods for advanced space detection and a global change study (Chap. 11).

The first author is in charge of all the concepts, the establishment of the first- and second-level titles, the guidance of each part and all chapters, the summary of the five characteristics of the polarization remote sensing of the ground, the extraction of the three regular characteristics of the atmospheric polarization remote sensing, and the opening of the five new frontier international cooperation fields of polarization remote sensing. The second author Bin Yang and the third author Feizhou

Zhang are in charge of the fifth and sixth chapters. The fourth author Yun Xiang is in charge of the third chapter, cooperating with the first author for the manuscripts of the second to fourth chapters. The fifth author Wei Chen is in charge of the ninth chapter. The first author is in charge of the other chapters, checks the manuscripts of each chapter and reviews for more than three times.

This book is a crystallization of the creative achievements accumulated by the first author's team for a long period of time concentrated on basic research, experiments, and teaching. Special thanks should be given to Professor Hu Zhao for the fourth chapter of the book, Professor Taixia Wu for the eighth chapter of the book, and Professor Guixia Guan for the tenth chapter of the book. The first author expresses his gratitude to all the contributors with sincere respect. The first author expresses his gratitude to the relevant state departments for their financial support.

Finally, I would also like to thank Qingxi Tong, Academician of the Academy of Sciences, Xianlin Liu, Academician of the Academy of Engineering, and Xiaowen Li, Academician of the Academy of Sciences for their review, suggestions, and recommendations.

This book has been written since 2015. Although it has been revised, screened, and refined in the past 4 years, due to the limited knowledge of the author, it is still difficult to avoid mistakes. Please give advice and point out my error, my email is lyan@pku.edu.cn.

October 2019

Dr. Lei Yan
Written at Weiming Lake
Peking University

Afterword

The final draft of the book is a mark of the miles of my life. It has been 17 years since I started to pay attention to polarization remote sensing. It has been 14 springs and autumns to actually launch basic theoretical research on polarization remote sensing.

Science is a stream, a trickle; little by little, drop hollows the stone

Since 1998, when I finished my first monograph "structural control of resources, environment and ecological giant system" from the field of electronic and electrical automation to the field of geosciences, I began to comprehensively examine my "territory" of remote sensing. After more than 2 years of tracking and observation of polarization remote sensing research carried out by Professor Yunsheng Zhao of Northeast Normal University, based on my background of optoelectronics and electromagnetics, I realized that polarization, the unique role of this physical phenomenon, can become a virgin land to be cultivated urgently for remote sensing and optical observation and is expected to become an indispensable supplement branch of conventional remote sensing and optical imaging observation. In 2001, I sent doctoral students to Northeast Normal University for the first time for three months, which verified that the field experiment data can be reproduced, which means that there are rules to explore; at the same time, it was found that the measurement instrument data can only be recorded and read manually, and then input into the computer processing and analysis, the efficiency and reliability are affected. Under the traction of the polarization remote sensing demand of Zhao's team, our team compiled the instrument automatically computer interface. Thus, the bottleneck of automatic data acquisition and computer analysis has been completely solved, making more than 100000 sets of original data accumulated manually in the past 13 years, and more than 300000 sets of measurement data, including more than 200000 sets of field joint measurement data, plus nearly 100000 sets of flight data of our team. Thus, the strong data onto automatic acquisition and analysis and the common field experiment foundation are established for the study of polarization remote sensing theory.

Secondly, in 2002, Yunsheng Zhao and I went south to Hefei, researcher team of Anhui Institute of Optics and Mechanics, Chinese Academy of Sciences, the research unit of polarization remote sensing instrument, held the long-term research strategy seminar of polarization remote sensing for the first time, and determined that the Northeast Normal University focuses on the acquisition and experimental analysis of field data outside polarization remote sensing, and the Institute of Optics and Safety, Chinese Academy of Sciences focuses on the development and indicators of polarization remote sensing instrument It is verified that Peking University focuses on the establishment of polarization remote sensing theory, mechanism interpretation, link work under the guidance of the theory of instrument indicators and ground feature parameters based on the data and instrument requirements of the outfield features; and recommends that Peking University team be responsible for convening all parties to carry out the continuous annual consultation mechanism to focus on attracting the domestic scientific community to participate in polarization remote sensing research. This consultation system has been maintained in the weakest period and has gradually diversified forms and developed continuously: In 2004, our team supported the integration of Xingfa Gu teacher's team of Remote Sensing Application Institute of Chinese Academy of Sciences (CAS) and polarization remote sensing instrument team of Anhui Optics and Precision Mechanism Institute of CAS with all the achievements of the first doctoral dissertation on polarization remote sensing mechanism in China, and applied to the state for project approval successfully. In 2005, we and Northeast Normal University; in 2006, we successfully attracted the domestic excellent team of polarization optical devices, the team of Professor Jianyi Yang and Yubo Li from Zhejiang University to join in supporting polarization remote sensing observation and research, and in 2008, we won the first team of polarization remote sensing devices jointly applied by the National Natural Science Foundation of China Objective: In 2008, he established academic contacts and talent exchanges with Zhongquan Qu team of Yunnan Observatory of Chinese Academy of Sciences on polarization observation and remote sensing polarization observation and sent each other graduate students to study the complementary mapping of surface atmospheric polarization remote sensing and planetary polarization observation; in 2007, he conducted bionic polarization navigation research with Professor Jinkui Chu, academician of Liding Wang of Dalian University of Technology and obtained the results in 2009: the first bionic polarization navigation project jointly applied by our team. Thus, the combination and cross of multiple teams of polarization remote sensing in China has been realized, which has established the basis of truth-seeking team cooperation beyond the economic interest relationship for the full implementation of polarization remote sensing in China and won the first prize of Beijing Science and Technology Progress Award (natural science category) in 2012 with the achievement of multiple team cooperation "systematic theory, methods and several discoveries of polarization remote sensing."

In terms of project support, due to the lack of national projects in terms of polarization, we have to find solutions respectively. Yunsheng Zhao and I am mainly national funds. In the aspect of aviation polarization data acquisition, Xingfa Gu's team gave us free help. In the world's first flight experiment aimed at the atmospheric polarization neutral point area, Beijing Xingtiandi Technology Co,

Ltd, the leader of the national aviation remote sensing industry alliances, has borne all the expenses of the flight experiment in Zhuhai free of charge. Chunfeng Zhang, the general manager, and Chao Zhang, the chairman of the board, know that such a flight will provide the experimental basis of us to overcome the atmospheric attenuation before coming. They have arranged a half month flight of us without hesitation. These have become an inexhaustible driving force for our continuous research.

Science is the fountainhead, moisten the soil, and nurture later learning

I remember that when Hu Zhao, the first polarization doctoral student, defended against 2003, strict experts judged his polarization remote sensing theory and density conversion theory, which basically failed to pass. Hu Zhao was so aggrieved that he wanted to give up. I talked to him for a month and decided to continue. We encouraged each other and persevered, so that he spent another year perfecting his thesis, and finally conquered all the judges and became the first doctor in the basic theory research of polarization remote sensing in China. His polarization non-contact estimation of the surface density of the Qilian Mountains and the moon is within 15% of the actual measurement error of the sample, which makes us deeply feel the important role of polarization remote sensing, and thus has the theoretical construction of the fourth chapter of this book. On this basis, Hu Zhao successfully applied for NSFC after graduation and achieved the deepening results.

The second Ph. D student Yun Xiang used hyperspectral polarization remote sensing for ground feature research. More than 30 rock density measurements and geological samples were measured. The accuracy was within the allowable range of engineering error, which built up our confidence, and thus the theoretical construction of Chap. 3 of this book. She was pregnant and ran around Changchun and Wuhan to prove the figure of polarization theory with various geotechnical samples, which was always engraved on the way of seeking polarization remote sensing.

Under their leadership, a group of postdoctoral and master's students have carried out arduous research on methods of remote sensing of ground objects, thus accumulating the second chapter of this book.

On the premise of breakthrough in the study of ground object polarization, I have noticed that atmospheric attenuation is the biggest error source of remote sensing. In the field of atmosphere, we use polarization scattering transmission attenuation to estimate aerosol thickness and atmospheric effect. Why can't we use polarization method to try to explore the law forbidden area of remote sensing such as atmospheric window? So I turned to Taixia Wu, the third doctoral student in polarized remote sensing, to the study of atmospheric attenuation. Half a year after his visit to the USA, he emailed me that he found that there was an area in the atmosphere where the polarization attenuation effects were zero. So it was difficult to measure the atmospheric effect on polarization. I asked him how he studied the atmosphere. He said that because the atmospheric attenuation affects the inversion of surface features. I said that if the polarized light carries the ground feature information, isn't it the new, low attenuation atmospheric window that we expect to observe or obtain the polarized ground feature information in the area where the

polarization effect is zero? This makes his doctoral project all deepen to the study of the neutral point region of atmospheric polarization. This is the basis of the theoretical breakthrough in Chap. 8 of this book. After graduation, he cooperated with us and applied to NSFC.

The fourth doctoral student Guixia Guan's polarization research started from bionic polarization navigation and found a large number of laws of atmospheric polarization pattern, which became the basis of theoretical breakthrough in Chap. 10 of this book. After graduation, she cooperated with us to preside over the application for in-depth research of NSFC, and all her graduate students joined the team of Peking University.

Based on the work of Taixia and Guixia, group of our master's and undergraduate students have been engaged in the observation of atmospheric polarization pattern, which has become the basis for the theoretical construction of Chap. 7 of this book.

Wei Chen, the fifth doctoral student, was sent to Zhanqing Li, an atmospheric remote sensing scientist and an atmospheric scientist at the University of Maryland, U.S., on the basis of the theoretical results of the atmospheric polarization model map and the atmospheric polarization neutral point region. Under the influence of Liang's team, we have achieved a breakthrough in the method of three-dimensional chromatography of atmospheric polarization effect and large-scale characterization of atmospheric particle polarization remote sensing, which has become the core theory in Chap. 9 of this book.

Bin Yang, the sixth doctoral student, and Mr. Yunsheng Zhao have carried out polarization remote sensing research on surface water, soil, and vegetation and cooperated with the international famous global biomass remote sensing inversion team to carry out relevant research, which has made very positive progress, thus forming the fifth and sixth chapters of this book together with Mr. Zhao. On this basis, he led the research team to prove the theory of polarization "strong light weakening" and "weak light strengthening" and solved the long-standing problem of polarization remote sensing.

Science is manna and nutrients, besten the fruit, comb the harvest

Since 2007, my students and I have to go out and come in every year to combine our polarization research results with international cutting-edge and hot issues, and attract the attention of peers at home and abroad. Our theory has begun to explain and guide the application of technology and methods in the field of related disciplines. The 7th International Workshop on solar, 2013 At the world's highest 3-year Global Conference on astronomical polarization observation of stars and planets, we were invited to make a report on the polarization remote sensing earth observation conference to lead the complementary and conversion of polarization observation means in the field of astronomy and remote sensing; we proposed the global comparison and objective enlightenment of polarization vector field, gravity field and geomagnetic field in the whole sky to determine the third earth The breakthrough of the whole field on the observation means of different astronomical

problems may be reported in the relevant organizations and conferences of atmospheric observation, environment, geology and geophysics, and our observation instrument "polarized remote sensing imaging" System "won the 2013 Geneva International Invention Gold Medal. It also exchanged visits with Professor Ansundi, chairman of Singapore Optical Society and Optical Research Center of Nanyang University of Technology and established the development plan of remote sensing and multioptical polarization instruments. Changyong Cao, director of NOAA National Calibration Center, USA, invited our Chinese team to join in, hoping to prove the irreplaceable role of remote sensing radiance reference to the moon by means of polarization observation, so as to realize the world problem of polarization "strong light weakening" filtering saturation and "weak light strengthening" highlighting extremely small fluctuation of radiance. At present, our Chinese team of scientists has been continuously involved in the observation and research for 5 years; Boston University famous remote sensing in the USA, Professor Yuri, an expert in vegetation inversion, and a team of European and American scientists and another group of international ecologists argued on PNAs in the USA about the positive–negative correlation between global vegetation biomass and C, N content, pointing out that polarized remote sensing is expected to become a unique screening method, and our Chinese scientists are invited to become the backbone to jointly correct and improve the basic theory of remote sensing inversion; polarized remote sensing objects. The systematic theoretical outlook of theory makes the USA, Britain, Ireland, Hungary, Austria, Australia, Singapore, Australia, etc., become the international arena for long-term or multiple interactive discussions, so as to achieve significant progress in polarization remote sensing and wider acceptance of polarization remote sensing methods and theories. This leads to the challenging and rich fruits of Chap. 11.

I am awed by all those who have participated in this arduous and fundamental exploration of natural laws and scientific methods. On the basis of what I have mentioned above, I put forward two bottleneck problems existing in the remote sensing observation, namely the limitation of the intensity of the electromagnetic spectrum reflected by the ground object at both ends and the attenuation error effect of the atmospheric window, and extracted the breakthrough progress of the three parts of the polarized remote sensing: first, the basis of "weak light enhancement" and "strong light weakening" of the polarized remote sensing of the ground object, so as to extend the detection area at both ends of the remote sensing, and explore Based on the analysis of the laws in the past ten years, I have summed it up into five characteristics of polarization remote sensing: multi-angle reflection physical characteristics (Chap. 2), multispectral chemical characteristics (Chap. 3), roughness and density structure characteristics (Chap. 4), information background high contrast filtering characteristics (Chap. 5), radiation transmission energy characteristics (Chap. 4) The six chapter. Secondly, the polarization method of atmospheric attenuation is accurately described, the law is discovered, and the new theoretical basis of atmospheric window is explored. The important connotation of atmospheric polarization remote sensing is obtained: the law of all sky polarization pattern and physical characteristics (Chap. 7), the regional law of atmospheric

polarization neutral point and the separation of ground air parameters (Chap. 8), and the law of all sky polarization vector field gas particle multi-angle observation of solid chromatography (Chap. 9). Thirdly, the latest development of polarization remote sensing application is given to prove the objectivity, uniqueness, stability, and repeatability of polarization remote sensing physics, so as to bear China's leading responsibility in the theory, method, and application of international polarization remote sensing physics. Therefore, it becomes the first chapter of the book: the physical basis of polarization remote sensing; and connects other chapters in series.

The above lament is for the feeling that the collection is in awe of all the contributors and grateful for the national basic research support projects.

The first Author Dr. Lei Yan
Originally written at a 30 hours flight to Santiago, Chile, November 11, 2014 (first time to be invited to present a polarization remote sensing report at the South American International Conference)
Revised at Weiming Lake, Peking University, October 4, 2019

Contents

Part I
Introduction

Chapter 1
Physical Rationale of Polarized Remote Sensing

Polarization, together with intensity, frequency, and phase, are the four main physical features of remote sensing using electromagnetic waves. This chapter discusses the physical rationale of remote sensing. For the two bottleneck problems we have in remote sensing, namely (1) restriction from the two ends of electromagnetic spectrum reflected by land objects and (2) atmospheric window attenuation difference, this chapter provides three breakthroughs: (1) the basis from which to support "bright light attenuation" and "weak light intensification" in the area of polarized remote sensing of land objects, this can greatly expand the detection range at both the dark and the bright ends of remote sensing data inversion; (2) accurate description of polarization methods and research on the rules of atmospheric attenuation, as well as exploration of the basis for new atmosphere window theory of atmosphere polarized remote sensing.

1.1 Polarization of Light

The development of remote sensing science and technology is now at a new stage. To be specific, theoretically it is shifting from simple description to quantitative research, from just describing the relationship between measured radiation values and phenomena on the land to quantifying their relationship around bidirectional reflectance and radiation, from forward radiative transfer models to quantitative inversion of radiative transfer models, and from focusing on separate wave ranges (for example, only research on visible, thermal infrared or microwave spectrum) to integrating wave spectrum ranges. From the view of technical development, it evolved from a single wave range to multiple wave ranges, angles, polarization, multi-temporal as well as multi-modal, and from single sensor to multiple sensor integration. Polarized remote sensing started to develop against this background and marks a relatively new remote sensing area which needs to be further studied.

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Polarization is defined as the asymmetry of vibration direction relative to spreading direction (Yao 2008). It is a unique feature of transverse electric and magnetic waves. Polarization is an important feature of electromagnetic wave. Objects on the land and in the atmosphere can produce their unique polarized signals during reflection, scattering and transmission, which means, polarization can reveal abundant information about objects. In nature, natural polarisers exist: for instance, smooth leaves of a plant, soil, water surface, ice, snow, cloud, fog, etc. cause reflection of sunshine from such polarisers result in polarization. Based on this feature, polarized remote sensing provides new and potential information for objects of remote sensing: polarized remote sensing has become a new earth observation method which is receiving more attention.

Polarization is initially introduced to the study of optics by Newton between 1704 and 1706. The term "optic polarization" was coined by Malus in 1809, and Malus also identified polarization in the laboratory as a phenomenon. Maxwell created optical electromagnetic theory between 1865 and 1873, and this theory explained optical polarization in essence. According to electromagnetic theory, light is a transverse electric and magnetic wave and electric field vibrates vertically to the direction of light transmission. Based on the trajectory of electric field vibration, it has five polarization states: natural light (non-polarized light), linear polarized light, partial polarized light, circularly polarized light and elliptical polarized light (Ye et al. 2005).

Natural light has the same vibration amplitude in all directions. It may vibrate in each direction that is vertical to its spreading direction with the same amplitude. If we decompose the light in all directions to only two vertical directions, then we can find that the vibration energy and amplitude in the two directions are the same. Linearly polarized light means that, in the vertical plane to the direction of transmission, the electric field intensity vector only vibrates in a certain direction. Partially polarized light can be viewed as a mix of natural light and linearly polarized light, namely it has vibration range in a certain direction that is superior to other directions. Circularly polarized light and elliptical polarized light refer to light whose electric field intensity vector end has a round or elliptical trajectory on the plane vertical to the light transmission direction. To describe polarized light, we adopt the time average of the two components of light (for example, values along the x-axis and y-axis) that are vertical to the transmitting directions. Light spreading towards a certain direction can be viewed as a composition of two light waves along the x-axis (horizontal axis) and y-axis (vertical axis). The polarized electrical vector of polarized light can be measured by combination of x and y-values. At a stable vibration with a single frequency, the two components are also in a stable state and have a certain relationship with each other. So the final ends of the electrical vector will have a three-dimensional trajectory, and its location at a certain moment is called the "moment trail".

Plane electro-magnetic waves are transverse, where electric field and magnetic field are orthogonal, so when light travels along the z-direction, there are only x and y-components in the electric field. The electric field component of plane magnetic wave can be described as:

$$E = E_0 \cos(\tau + \delta_0) \tag{1.1}$$

Here, $\tau = \omega t - kz$, and this equation can be further broken down to:

$$\begin{cases} E_x = E_{0x} \cos(\tau + \delta_1) \\ E_y = E_{0y} \cos(\tau + \delta_2) \\ E_z = 0 \end{cases} \tag{1.2}$$

To obtain the curve comprised of end points of electric field vectors, we remove parameter τ, so we get:

$$\left(\frac{1}{E_{0x}}\right)^2 {E_x}^2 + \left(\frac{1}{E_{0y}}\right)^2 {E_y}^2 - 2\frac{E_x}{E_{0x}}\frac{E_y}{E_{0y}} \cos\delta = \sin^2\delta \tag{1.3}$$

Herein, $\delta = \delta_2 - \delta_1$, the equation above is an elliptical equation: because the determinant of coefficients is above zero, the end-points of electric field vectors will compose an elliptical track. This means that, at any moment, in the spreading direction, vector ends of all points in the space compose an elliptical shape when projected to the *x*-*y* plane. Such an electro-magnetic wave is referred to as elliptical polarized light. Other polarization states are special cases of elliptical polarized lighting. Figure 1.1 shows elliptical polarization with different values of phase difference.

(1) $\delta = 0$ or integer multiples of $\pm\pi$

With $\delta = \delta_2 - \delta_1 = m\pi (m = 0, \pm 1, \pm 2, \ldots)$, the ellipse will degenerate to a straight line, and we have:

$$\frac{E_y}{E_x} = (-1)^m \frac{E_{0y}}{E_{0x}} \tag{1.4}$$

Electrical vector E has consistent direction and is called linear, or plane polarization.

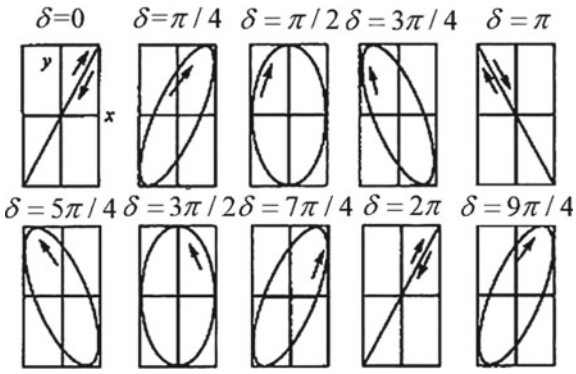

Fig. 1.1 Elliptical polarization with different values of phase difference