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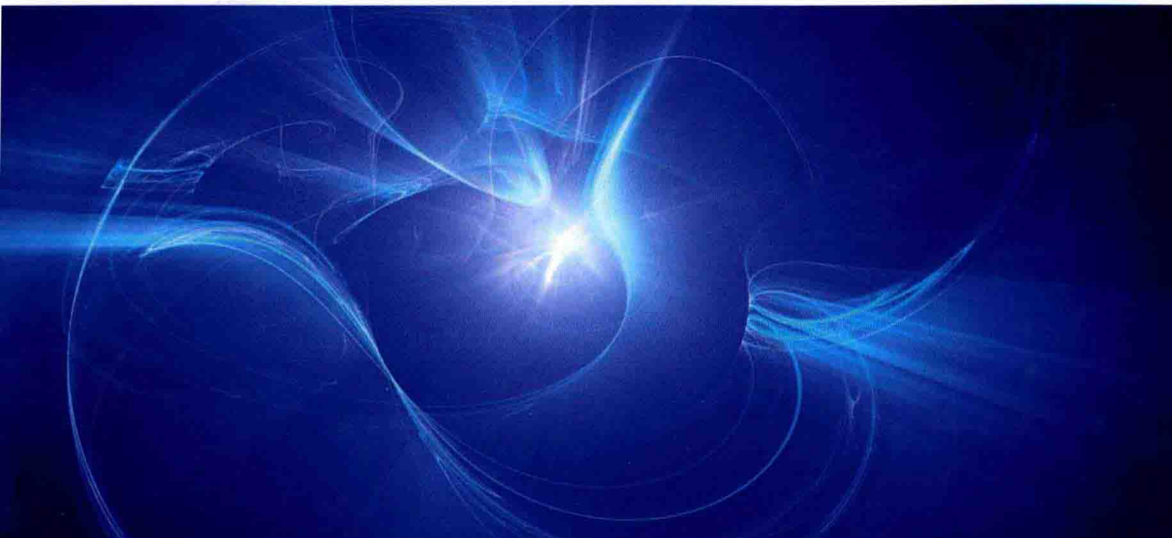
光学与光子学丛书

All-Optical Switches Based on Nonlinear Optics

基于非线性光学的全光开关

Chunfei Li（李淳飞）



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Biography of Prof. Chunfei Li

Chunfei Li graduated from Harbin Institute of Technology (HIT) in 1961, where he majored in Physics and Electronics. From 1962 to 1965, he visited Jilin University to study Theoretical Physics. He was employed by the Physics Department of HIT, where he was successively promoted to be Lecturer (1978), Associate Professor (1982), and Full Professor (1985). From 1985 to 1998, he served as Chairman of Physics Department in HIT. After that he is a director of the Institute of Advanced Optics in HIT. Now he is a professor invited specially at South China Normal University in Guangzhou. From 1987 to 1989, Prof. Li was invited to be one of 70 members of the Chinese High Technology Specialist Committee, working in the group of information technology to preside over the research programs on optoelectronic devices in China.

Since 1979 Prof. Li began his research work on nonlinear optics, especially, optical bistability and optical instability. He was invited by Professor Hyatt Gibbs to work in this area at the Optical Sciences Center, University of Arizona, respectively in 1982, 1984 and 1996. In the following years, Prof. Li expanded his research work in China to excited-state nonlinear optics, optical limiting, nonlinear fiber-optics, chiral nonlinear optics, low-power all-optical switches and nanophotonics. He was one of pioneers in these research fields in China.

In the past 30 years, Prof. Li accomplished more than 300 papers published in famous international and domestic journals and 3 books: "*Nonlinear Optics*", "*Principles of All-Optical Switch*" and "*Photonics Technology and Application*" published by Chinese Publishing Houses. Because of his remarkable work, he was awarded 4 science prizes by the Chinese Government, respectively in 1987, 1996, 2000 and 2008. As a supervisor, he has tutored about 80 Ph. D and Master graduate students.

Prof. Li is a fellow of Chinese Optical Society and international member of OSA and SPIE. He was an editor serving for two Chinese journals: "*ACTA OPTICA SINICA*" and "*ACTA PHOTONICA SINICA*" and one international journal: "*Nonlinear Optical Physics and Materials*".

In the past 30 years, as a short-term visiting professor, Prof. Li has invited to work in a number of world-level research groups at University of Arizona, UC Santa Barbara, UC Los Angeles, University of Southern California, University of South Alabama, Penn State University, Tokyo University, University of Queensland and so on.

Prof. Li has rich experience in the international and domestic conferences. He was one of International Chairs of the First Conference on Nonlinear Optics at Hawaii, USA, in 1990. He was a Program Committee Member of the Conference on Optical Computing at Edinburgh, UK, in 1994 and an invited speaker in many international conferences. He has chaired 3 conferences on nonlinear optics in China, at Guangzhou in 1991; at Nanjing in 1993; and at Harbin in 1995, and has chaired 8^{th} Photonic Conference at Nanchang in 2012.

Preface

In 1960 the invention of the laser marked the human began to master the coherent-photon source. It means that photonics and photonic technology were born. Since then, the photonic technology and electronic technology began a long-term competition. Who will be the final winner? The currant competition results show that each of these two techniques has its own strengths and weaknesses.

The electronic technology in the 20th century has made brilliant achievements, for example, the computer, internet, and mobile phone etc. The wide application of electronic technology brings great changes to human life. That is because the electronic technology is good at digital information processing.

As for the photonic technology, it also has a great progress in the past 30 years. As we know, the photonic technology is particularly suitable for information transmission. In this respect it has many advantages: wide band, large capacity, parallel processing and fast speed. Now the optical-fiber communication has replaced the electrical-cable communication; the optical disc has replaced the magnetic disk in information storage technology; and the fiber grating sensor has replaced the semiconductor sensor in sensing technology. In addition, the solar cell and LED lighting push the green-energy-source technology fast developing.

Look at today's extensively used computer, its external equipment including the memorizers, displayers, input and output components, etc. have been totally changed to the photonic components. However, so far all of the computer's CPU is composed with electronic chips. Furthermore, today's optical fiber communication is a photoelectric hybrid technology, in which the signal transmission has changed to the all-optical technology, but the signal switching is still using the electronic technology. The underlying reason is that the optical switch (or optical transistor) cannot replace the electronic switch (or transistor) yet.

Photon technology, therefore, has not yet been overcome the last position in digital information processing, which is now occupied by electronic technology. If the photonic technology can capture this final position, it will gain the final victory. At that time, the all-optical switch will be used instead of the existing electronic switch. As a result, the all-optical communication and all-optical computation will be realized.

In the past half a century, the researchers in optical-physics field focused on the study of laser sources, however, in this century they may turn to "controlling light with light". The most importent subject is just all-optical switch. However, because the interaction between photons is too weak, a group of photons cannot directly control the other group of photons like the electronic transistor, the only way is to indirectly use the nonlinear-optics method. That means using a high-power light to change the optical parameters of medium (such as the refractive index), and then controlling the power of the signal light passing through the medium, and switching its outputted power between the low-level and high-level.

Scientists around the world spent half a century of time and a lot of money in the research of all-optical switches, but they met some inherent difficulties coming from the nonlinear optics: in order to achieve the all-optical switching, it requires a strong control-light power, which is much higher than the signal power; to reduce the switching power, it must pay the price for decreasing the switching speed and increasing the device loss; and the switch-off time is always longer than the switch-on time in about two order of magnitude. Therefore, so far there are not any all-optical-switch products available for application.

However, people have obtained a lot of research results and accumulated a wealth of experiences. The long-term research experience tells us that in order to make the practical all-optical switches we should use the nanophotonic technology and ultrafast-laser technology. Now the researches are focusing on the nanoscale all-optical switches.

In fact, all-optical switch is a very broad concept, which contains the intensity-type, space-type, time-type as well as the wavelength-type switching devices. Generally speaking, if a device can be discontinuously, rapidly and reversibly converted from a physical state to another using a pure optical method, this device is called all-optical switch.

The purpose of this book is to summarize the research results, systematically introduce the physical thought, basic principle and main application of various optical switches, which were studied by scientists in the past half century. The book also contains the author's contributions in the research of all-optical switches based on nonlinear optics in the past 30 years.

In last ten years, author offered a new course named "Principle of optical switches" to the graduate students in Harbin Institute of Technology and South China Normal University. This book' writing is based on lectures of the course. The author makes every effort to highlight the physical concepts and make them easy to understand. Having certain knowledge of optical physics, including laser principle, nonlinear optics, optical interferometers, etc., the readers can easily read this book.

The content of this book is divided into 10 chapters. Chapter 1 introduces the importance, classification and parameter of optical switch, and points out the research direction of the all-optical switch; Chapter 2 gives the basic knowledge of nonlinear optical physics and materials for all-optical switches; Chapter 3 introduces the electricity-controlled optical switches, which are available in the market; Chapter 4 studies the optical bistable device (OBD) including the pure optical OBD and the electro-optical hybrid OBD, in addition the instability of OBD; Chapter 5 discusses the nonlinear interferometer all-optical switches as a kind of space-type AOSs; Chapter 6 introduces the nonlinear fiber grating AOS, which is one of intensity-type AOSs; Chapter 7 shows the nanoscale AOS including the nanoscale waveguide AOS, the photon crystal AOS and the surface plasmonic AOS; Chapter 8 discusses the optical flip-flop, a time-type AOS, and the wavelength convertor, a wavelength-type AOS; Chapter 9 talks about optical-limiting optical switches, which is a transmittance switch used for preventing laser injure to eyes. Finally, Chapter 10 discusses the applications of AOSs in all-optical communication networks.

Actually, the optical switches have many other applications besides in optical communication, for example in computer technology, sensing technology, as well as optical metering, and optical storage. These applications have not been included in the book because those applications are immature yet.

I hope this book can make the readers systematically understand the basic principles of all-optical switches, and can encourage the young readers having interest to engage in the future research of all-optical switch.

The author sincerely thank professors H. M. Gibbs, Y. R. Shen, E. Garmire, and P. W. Smith, to guide me in my early works on optical bistability; thank Chinese professors (Academician of Chinese Academy of Sciences) Wang Dahang, Wang Zhijiang, Liu Songhao and Wang Qiming to encourage me in research on nonlinear optics and all-optical switch. I should also thank my 80 PhD and Master students in Physics Department, Harbin Institute of Technology to join the research works in my group. The book also contains their hard work results.

My teaching and research work were very busy in the past decades; I only spent some spare time in writing this book. I sincerely invite my readers provide some suggestions to further modify the book, making it a valuable textbook for graduate students and reference book for researchers.

Chunfei Li

On November 15, 2014

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Chapter 1 Introduction to Optical Switch

In this chapter, we discuss the significance of optical switch, introduce the classification and the parameters of optical switch, and point out the necessary technical indexes of practical all-optical switches. In order to achieve these technical indexes, the only way out is to study and develop the nanoscale all-optical switches with low power, high speed and low loss.

1.1 Importance of Optical Switch

1.1.1 Optical Switch is a Demand of Optical Physics Development

1.1.1.1 Development Tendency of Optics and Photonics

As is known to all, the light wave is part of the electromagnetic wave; its frequency range is within 10^{11}~10^{16} Hz, including terahertz (THz), infrared, visible, and ultraviolet light wave. It likes other electromagnetic waves to comply with the Maxwell equations. The light wave also can be regarded as a combination of photons. The photon is a kind of fundamental particles. It likes other fundamental particles, as well as to obey the Schrodinger equations, but it has no quality and is not charged. Figure 1.1 shows the frequency division of electromagnetic wave, and the corresponding methods used in the communication.

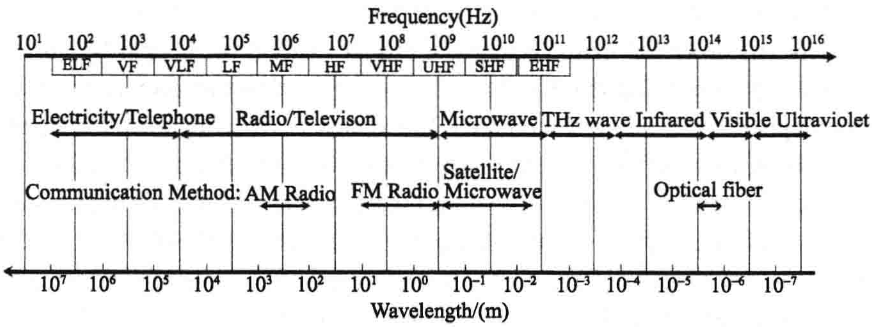

Figure 1.1 Electromagnetic wave frequency division and the corresponding methods used in communication

Optics and electromagnetism, both born in the 18th century, are two branches of the physics. The development process of the photonics is very similar to that of the electronics as shown in Figure 1.2, which shows development roadmaps of photonics and electronics [1].

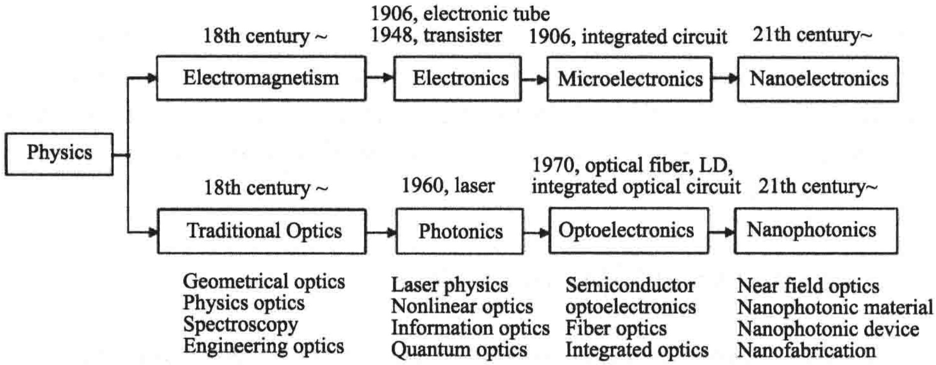

Figure 1.2 A comparison between two development roadmaps of photonics and electronics

Firstly, let us brief review the history of the electronics. On the basis of electromagnetism, in the 19th century, various electronic products and technologies such as the generator, motors, electric car, electric lamp, electric telephone, radio communication etc. were invented, and then people said that the human has been entered into the "Electrical Age".

At the beginning of 20th century, the invention of the electronic tube marked the people knew how to produce and control electrons, thus a new discipline-Electronics was established. The development stages of electronics can be divided into two: one is Vacuum-Tube Electronics since the invention of the vacuum tube in 1906; and the other is Semiconductor Electronics since the invention of the transistor in 1948.

In 1960, the invention of the integrated circuit marked the people began to master the technology integrating the micron-scale electronic elements such as the transistors, resistor, capacitor etc. into a silicon chip. Since then Electronics was developed to Microelectronics, as a result, brilliant achievements in microelectronic technology flourished, for instance, the radio, television, tape recorder, video, video cameras, radar, microwave communication, electronic computers, as well as the electronic internet. In summary, the electronic technology has brought great changes to human life, so in later of 20th century, people declared: "The human has entered the Electronic Age."

Unfortunately, nowadays the development of microelectronics has met some bottlenecks: the miniaturization of electronic chip has been restricted by the diffraction limit. Recently, people are studying the nanoscale electronic components, such as the carbon