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(影印版)

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远程通信中的非线性光学

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《国外物理名著系列》(影印版)专家委员会名单

（按姓氏笔画排序）

国外物理名著(影印版)系列序言

对于国内的物理学工作者和青年学生来讲，研读国外优秀的物理学著作是系统掌握物理学知识的一个重要手段。但是，在国内并不能及时、方便地买到国外的图书，且国外图书不菲的价格往往令国内的读者却步，因此，把国外的优秀物理原著引进到国内，让国内的读者能够方便地以较低的价格购买是一项意义深远的工作，将有助于国内物理学工作者和青年学生掌握国际物理学的前沿知识，进而推动我国物理学科研和教学的发展。

为了满足国内读者对国外优秀物理学著作的需求，科学出版社启动了引进国外优秀著作的工作，出版社的这一举措得到了国内物理学界的积极响应和支持，很快成立了专家委员会，开展了选题的推荐和筛选工作，在出版社初选的书单基础上确定了第一批引进的项目，这些图书几乎涉及了近代物理学的所有领域，既有阐述学科基本理论的经典名著，也有反映某一学科专题前沿的专著。在选择图书时，专家委员会遵循了以下原则：基础理论方面的图书强调“经典”，选择了那些经得起时间检验、对物理学的发展产生重要影响、现在还不“过时”的著作（如：狄拉克的《量子力学原理》）。反映物理学某一领域进展的著作强调“前沿”和“热点”，根据国内物理学研究发展的实际情况，选择了能够体现相关学科最新进展，对有关方向的科研人员和研究生有重要参考价值的图书。这些图书都是最新版的，多数图书都是 2000 年以后出版的，还有相当一部分是 2006 年出版的新书。因此，这套丛书具有权威性、前瞻性和应用性强的特点。由于国外出版社的要求，科学出版社对部分图书进行了少量的翻译和注释（主要是目录标题和练习题），但这并不会影响图书“原汁原味”的感觉，可能还会方便国内读者的阅读和理解。

“他山之石，可以攻玉”，希望这套丛书的出版能够为国内物理学工作者和青年学生的工作和学习提供参考，也希望国内更多专家参与到这一工作中来，推荐更多的好书。

杨国桢

中国科学院院士

中国物理学会理事长

2007 年 3 月 20 日

Preface

In today's backbone networks, data signals are almost exclusively transmitted by optical carriers in fibers. The continents and the whole world come closer together by a large number of optical fibers lying on the bottom of the oceans. Applications like the internet demand an increase of the available bandwidth in the network and reduction of costs for the transmission of data. Linear optics is, in principle, a special case of the much wider field of nonlinear optics. Nonlinearity can only be neglected if the optical intensities are small. With the increasing data rates, the optical amplification of the signals, and the incorporation of techniques like dense wavelength division multiplexing (DWDM) nonlinear optical effects become very important for system design since these effects can cause severe problems. On the other hand, the same effects offer the possibility for very fast all-optical signal processing.

This book tries to give an introduction to the fascinating field of optical telecommunications. In order to write a useful text for students, technicians and researchers working in the field, the technical aspect as well as the physical background of the different effects is described in detail. In most cases the easiest way to explain the physics of nonlinear optics was chosen. Nevertheless, an attempt was always made to integrate the latest research results.

Although the whole text was carefully written and corrected several times it could be possible that some mistakes were overlooked. I apologize for this and I am very thankful for everybody who informs me about mistakes.

First of all I want to thank my family, Kerstin and Clara for their support and understanding. Special thanks go to R. Fischer for the relief he gave me on important showplaces beside. I am deeply grateful to Prof. W. Glaser from the Humboldt University in Berlin and to Prof. J. Reif from the Brandenburgische Technische Universität in Cottbus who gave me the opportunity to engage in the research of nonlinear optics.

Special thanks to all the colleagues who discussed special subjects with me and who always had an open ear for any kind of problems: Dr. R. Schmid (BTU Cottbus), W. Ruhland and M. Messollen (FH Telekom Leipzig).

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Last but not least I want to thank G. Biermann, from the library of the FH Telekom Leipzig, who provided me with the required literature, as well as the editors and production team from the Springer Verlag for their kind support.

Leipzig, October 2003 *Thomas Schneider*

Contents

1. Introduction

In the early days of optical telecommunications the attenuation and dispersion of the fiber were the most important aspects that determined the bit rate and the maximum distance of the links in communication systems. New fiber designs and a more or less intelligent dispersion management could rectify these linear effects. The nonlinearity of an optical fiber is very weak; it depends on the intensity of the transmitted signals and the interaction length. Due to the fact that only rather small distances between a transmitter and receiver were bridged optically, nonlinear effects played only a marginal role in special fields such as long haul undersea cable systems.

In the last few years the picture has completely changed. Responsible for this fact are especially two reasons: the ever increasing demand of bandwidth due to "packet oriented" applications like the internet, and the invention of optical amplifiers. This prediction will be substantiated in the following in more detail.

The bit rate in the communication systems in the 1980s was 155 Megabit per second (Mbit/s), ten years later it increased to 2.5 Gigabit per second (Gbit/s). Although 10 Gbit/s is being used today, the change for 40 Gbit/s is already planned and laboratories have show data rates up to a few Terabit per second (Tbit/s). Since the middle of the 1990s, optical telecommunication devices have been transmitted more than one wavelength over a fiber span to better exploit the usable bandwidth of optical fibers. The technique, dense wavelength division multiplexing (DWDM), transmits different channels at the same time in one fiber with different carrier wavelength.

Historically speech signals were transmitted via a virtual link between the transmitter and receiver through the network. The link lasted as long as the transmission was continued and a very high percentage of telephone conversations took place over a rather small distance. Contrary to this, the packets of the internet are transmitted over the communication networks world wide. Therefore not only the data rate of the systems increased, the distance over which the data signals had to be transmitted increased as well.

In order to reduce the costs for the transmission, it was necessary to minimize expensive elements like transmitters, receivers and regenerators in the optical network. At the same time the maximum data rate and transmission distance had to be increased drastically. This goal could be reached with the invention of the erbium-doped fiber amplifier (EDFA). Since this device allowed the amplification of the signal in the optical domain, the transformation into the electrical domain was no longer necessary. Hence a receiver, transmitter, and regenerator were spared with every optical amplifier.

On the other hand, an amplifier adds noise to the signal. With the increasing transmission distance, bit rate and number of amplifiers, the noise in the system will therefore increase. Since the bit error rate (BER) of the system depends on the signal to noise ratio, the signal power had to be increased. With use of the optical amplifiers, the drastically increased intensity and the interaction length together with the higher bit rates of current systems lead to a much higher impact of nonlinear effects onto the system design.

Another reason for the rise of nonlinear effects in optical communication systems is the very small attenuation the signal experiences in modern fibers together with the rather small core area in which the signal is guided. Hence, the high powers and very high intensities required for a particular BER will decrease very slowly and are amplified again with each EDFA. Assume, for instance, a DWDM system with 100 WDM channels and an input power of 3 mW each, propagating in a single mode fiber with an effective core area of 80 μm^2 and an attenuation constant of $\alpha = 0.2$ dB/km. The intensity in the core of the fiber is then 3.75×10^9 W/m^2, and will still be $\approx 3 \times 10^9$ W/m^2 after a distance of 5 km.

The nonlinearity is a fundamental physical property of the fiber. The highest bit rate that can theoretically be transmitted without an error over a classical (linear) link – like a copper wire or a wireless channel – depends only on the usable bandwidth and the signal to noise ratio. In optical fibers this bit rate is limited instead by the nonlinearity of the fiber.

A variety of different nonlinear effects can occur in optical fibers, all of them with different influences on the communications link. The self-phase modulation (SPM), for instance, leads to a change in the dispersion behavior in high-bit-rate transmission systems; the cross-phase modulation (CPM or XPM) and the Raman and Brillouin scattering implicate a decreasing of the signal to noise ratio; and four-wave-mixing (FWM) in dispersion-shifted fibers will increase the cross talk between adjacent channels.

On the other hand, the same nonlinear effects offer a variety of possibilities for ultrafast all-optical switching, amplification and regeneration. Currently, the whole spectrum of signal processing in the electrical domain and much more can, in principle, be carried out in the optical domain with the help of nonlinear effects. With solitons, for instance, it is possible to transmit optical pulses over extremely large distances without distortion. The FWM offers the possibility for a pure optical wavelength conversion. With an ultrafast optical grating that can switch optical signals in a few femtoseconds (10^{-15} s), the so called mid span spectral inversion can compensate the distortions of the optical pulses completely. Nonlinear effects like the FWM and the Raman and Brillouin-scattering are able to amplify optical signals in areas

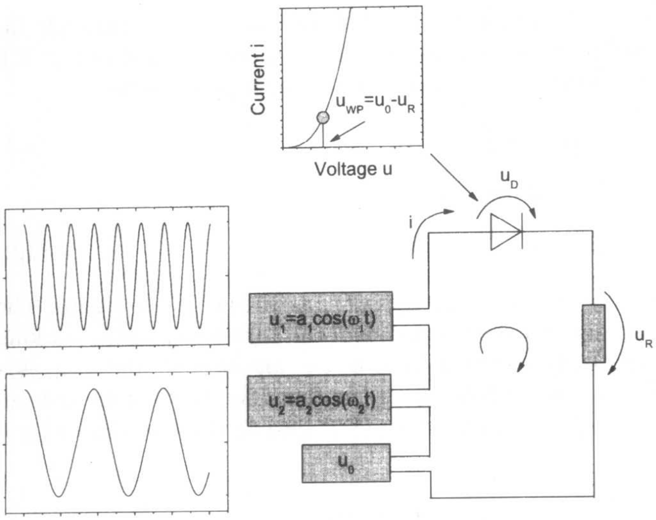

Fig. 1.1. Current diagram with a diode as nonlinear element

that can never be reached by EDFA's. Recent world records where data rates of a few Terabit per second (10^{12} bit/s) were transmitted over distances of thousands of kilometers would have been unthinkable without distributed Raman amplifiers.

With compact nonlinearities offered by highly nonlinear fibers, semiconductor optical amplifiers, and nonlinear photonic crystal microdevices [1], it may be possible to integrate some of these functionalities into small compact devices.

Nonlinear optics is the area of optics in which the response of a material system on an applied optical field is not linear and, hence, the superposition rule no longer holds. In other words, this means that different optical waves propagating in a nonlinear material are not independent of each other. They can not be simply added, like in the linear case, but the generation of harmonics and the mixing between them has to be considered.

Nonlinearity is not only responsible for the behavior of electromagnetic waves in the visible part of the spectrum, nonlinear dependence exists in electrical devices installed in circuits as well. Let's assume two alternating currents with different frequencies are propagating in a wire. If the frequencies are not too close together – so that fading can be neglected – and the intensities are not too high, both currents are propagated independently of each other in the medium. The two currents will only experience an attenuation, and the frequencies are the same at both ends of the wire. If, instead, a device like a simple diode is installed into the wire then the behavior is much more complicated. Figure 1.1 shows the dependence between the voltage and the current of a theoretical diode and the circuit diagram.

The current through the diode and therefore the current through the resistor depends nonlinearly on the voltage, as shown in the inset of Fig. 1.1. This nonlinear dependence can be approximated by a power series:

$$i = c_0 + c_1 u_\mathrm{D} + c_2 u_\mathrm{D}^2 + c_3 u_\mathrm{D}^3 + \dots \tag{1.1}$$

The voltage that falls off over the diode is:

$$u_\mathrm{D} = u_1 + u_2 + u_0 - u_\mathrm{R} \tag{1.2}$$

with $u_1 = a_1 \cos(\omega_1 t)$ and $u_2 = a_2 \cos(\omega_2 t)$, as shown in the figure. The voltage difference $u_0 - u_\mathrm{R} = u_\mathrm{WP}$ is required for the adjustment of the working point and is assumed to be constant, c_0 is a constant as well, and $c_1 u_\mathrm{D}$ is a linear term that is only responsible for attenuation. The first nonlinear term in (1.1) is therefore $c_2 u_\mathrm{D}^2$. If we introduce (1.2) into the first nonlinear term of (1.1), the result is:

$$c_2 u_\mathrm{D}^2 = c_2 \begin{bmatrix} \frac{1}{2}a_1^2 + \frac{1}{2}a_2^2 + u_\mathrm{WP}^2 \\ +2a_1 u_\mathrm{WP} \cos\omega_1 t + 2a_2 u_\mathrm{WP} \cos\omega_2 t \\ +a_1 a_2 \cos((\omega_1 + \omega_2)t) + a_1 a_2 \cos((\omega_1 - \omega_2)t) \\ +\frac{1}{2}a_1^2 \cos 2\omega_1 t + \frac{1}{2}a_2^2 \cos 2\omega_2 t \end{bmatrix} \tag{1.3}$$

In the first row of (1.3), there are constant terms with $\omega = 0$, whereas the second row contains the original frequencies. In the third row the sum and difference frequencies will be found and the last row contains frequencies twice the input frequencies representing an effect called the second harmonic. The second nonlinear term of (1.1) will deliver:

$$c_3 u_\mathrm{D}^3 = c_3 \begin{bmatrix} f(\omega = 0) \\ +f(\omega_1) + f(\omega_2) \\ +f(\omega_1 + \omega_2) + f(\omega_1 - \omega_2) \\ +f(2\omega_1 + \omega_2) + f(2\omega_1 - \omega_2) \\ +f(\omega_1 + 2\omega_2) + f(\omega_1 - 2\omega_2) \\ +f(2\omega_1) + f(2\omega_2) \\ +f(3\omega_1) + f(3\omega_2) \end{bmatrix} \tag{1.4}$$

Due to the nonlinear element in the electric circuit, the two frequencies are no longer independent of each other and the current will consist of sum, difference, and the harmonics of the original frequencies. This behavior is always the same whenever nonlinearities come into play, for instance due to the nonlinear behavior of gutters or aerial masts for the mobile communication signals, or as a result of the nonlinear function of an amplifier. For the radio frequency range these phenomena are called mixing or intermodulation, whereas for the visible range of the electromagnetic spectrum the term nonlinear optics will be used.

This book is divided into three parts, the first part is an introduction to linear and nonlinear optics as well as optical telecommunications. The