PHOTONICS

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Advanced Opto-electronic Devices

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1 **Advanced Optoelectronic Devices**
By D. Dragoman and M. Dragoman

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Preface

Optoelectronics will undoubtedly play a major role in the applied sciences of the next century. This is due to the fact that optoelectronics holds the key to future communication developments which require high data transmission rates and extremely large bandwidths. For example, an optical fiber having a diameter of a few micrometers has a bandwidth of 50 THz, where an impressive number of channels having high bit data rates can be simultaneously propagated. At present, optical data streams of 100 Gb/s are being tested for use in the near future.

Optoelectronics has advanced considerably in the last few years. This is due to the fact that major developments in the area of semiconductors, such as heterostructures based on III-V compounds or mesoscopic structures at the nanometer scale such as quantum wells, quantum wires and quantum dots, have found robust applications in the generation, modulation, detection and processing of light. Major developments in glass techniques have also dramatically improved the performance of optoelectronic devices based on optical fibers. The optical fiber doped with rare-earth materials has allowed the amplification of propagating light, compensating its own losses and even generating coherent light in fiber lasers. The UV irradiation of fibers has been used to inscribe gratings of hundreds of nanometer size inside the fiber, generating a large class of devices used for modulation, wavelength selection and other applications.

The aim of this book is to describe the optoelectronic devices that have resulted from these scientific and technological developments. The book focuses on the physics and modeling of the devices as well as on their applications, experimental evidence and their limitations.

The reader should be familiar with the basics of semiconductors as well as the fundamentals of electromagnetic theory. The book is addressed to advanced undergraduate and graduate students as well as to researchers in the field of semiconductors, optoelectronics and electromagnetics.

Chapter 1 describes briefly the fundamentals of electromagnetic field theory in linear and nonlinear media, background which is necessary to understand the subsequent chapters. This first chapter is not simply a brief presentation of electromagnetic field theory; its aim is to provide the main theoretical support for the book. Also some basic devices such as the directional coupler, Bragg reflectors and the distributed feedback laser are presented. Therefore, the reader is advised to read this chapter carefully. Many references are made to this chapter later throughout the book.

Chapter 2 is dedicated to semiconductor and fiber lasers. Nowadays, the semiconductor laser is the most studied semiconductor device and therefore this chapter is quite extended. The reader is advised to read this chapter to understand how semiconductors work on the nanometer scale and what physical effects and laser configurations are used to generate light. There are many semiconductor lasers based on the inversion of the population of an active layer, but the reader will observe that there are also unipolar semiconductor lasers without inversion, for example, based on tunneling. Different fiber laser configurations used to generate coherent optical pulses, in particular optical solitons, are also presented. Research efforts are concentrated towards lowering the threshold current, increasing the modulation bandwidth and stabilizing the laser emission in semiconductor lasers, as well towards the development of light sources in new wavelength intervals, already covered by modulators or photodetectors.

Chapters 3 and *4* are dedicated to the modulation and detection of light. The reader will discover the large number of physical effects exploited to modulate and detect the light. In nanometer scale devices unexpected effects appear which can be used for light modulation or photodetection. Among them is the exciton, which in a normal semiconductor has a significant absorption spectrum only at very low temperature, but in mesoscopic devices this spectrum is present even at room temperatures; modulation of the absorption spectrum can be used to change the index of refraction and to modulate the light. Nowadays, more than 100 GHz modulation/detection of light is achievable.

Chapter 5 is dedicated to devices that multiplex/demultiplex the optical information. The reader will see how tens or hundreds of high speed information channels can be simultaneously sent through a single fiber and how from this huge data stream the optical information can be recovered. All of the various multiplexing/ demultiplexing possibilities – in wavelength, time and polarization – are discussed.

Chapter 6 is dedicated to the processing of light. First, it is shown how ultrafast optical signals can be shaped, and in particular compressed. Then it is shown how optical signals can be transmitted, memorized and used as input for optical logical operations using semiconductor devices such as spatial light modulators or SEEDs, which can also be used to build an all-optical computer. The last part of this chapter is dedicated to optical computing of integral transforms of signals.

Although the devices are generally presented according to their most common application, some of them can perform different tasks. Almost 500 references are listed for further information. Of these, 90% are from 1994 or later!

We have tried to write this book such that it is neither a collection of formulas nor a gallery of devices. We have tried to explain the physical concepts and laws which have produced such a remarkable advancement of optoelectronic devices in the last few years and, based on these, we have presented the resulting devices, their characteristics, and their advantages and disadvantages. Inevitably, not all the new devices could be included in the book. The selection was mainly made according to the physical concepts or new technical ideas.

Part of this book was taught as a course at the Master in Science level at the University of Bucharest, Faculty of Physics, Solid State Physics Department in 1997.

We thank Prof. J.P. Meunier from Saint-Etienne University for his help and encouragement to write this book and to Prof. K.-H. Brenner from Mannheim University for his hospitality at the Department of Optoelectronics, where the book was finished.

One of us (M. D.) acknowledges Prof. D. Jäger from Duisburg University for many discussions about the physical meaning of electromagnetic fields and device modeling at high frequencies.

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Daniela Dragoman
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Contents

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1. Basic Concepts of Optoelectronic Devices

1.1 Maxwell's Equations in Linear Media

Optoelectronic devices are structures in which the electromagnetic field described by Maxwell's equations and the quantum mechanical laws for the wavefunction of the charge carriers cooperate in order to generate, propagate or detect optical fields.

The laws of quantum mechanics appear explicitly in the description of optoelectronic devices based on mesoscopic structures and therefore will be presented briefly at the beginning of Chap. 2 in connection with the definition and characteristics of structures with mesoscopic dimensions. However, Maxwell's equations and their solution in dielectric waveguides form the basis of the description of any optoelectronic devices including quantum ones. Therefore, the present chapter is entirely dedicated to Maxwell's equations and their solutions for coupled, periodic, linear and nonlinear dielectric media. We will focus first on linear media, i.e. media in which the dielectric constants are independent of the propagating electromagnetic fields, while nonlinear media will be treated in Sect. 1.5.

1.1.1 Maxwell's Equations in Linear and Inhomogeneous Media

Maxwell's equations are:

$$\begin{aligned} &\nabla \times \boldsymbol{E} = -\partial \boldsymbol{B} / \partial t, \\ &\nabla \times \boldsymbol{H} = \partial \boldsymbol{D} / \partial t + \boldsymbol{J}, \\ &\nabla \cdot \boldsymbol{B} = 0, \\ &\nabla \cdot \boldsymbol{D} = \rho, \end{aligned} \tag{1.1}$$

where $\boldsymbol{E}$ and $\boldsymbol{H}$ are the electric and magnetic fields, $\boldsymbol{D}$ and $\boldsymbol{B}$ are the electric displacement and magnetic induction field, respectively, ρ is the density of charge and $\boldsymbol{J}$ is the current density vector. The four field vectors which appear in Maxwell's equations are related through two constitutive equations that describe the response of the medium to the electromagnetic field excitation. These are $\boldsymbol{B} = \hat{\mu}\boldsymbol{H}$ and $\boldsymbol{D} = \hat{\varepsilon}\boldsymbol{E}$ with $\hat{\mu}$ and $\hat{\varepsilon}$ the magnetic permeability and electric permittivity tensors, respectively. Since throughout the book we will be mainly concerned with electromagnetic propagation problems we can safely assume throughout that $\rho = 0$ and $\boldsymbol{J} = 0$. Moreover, for isotropic media, which represent the most common situations in optoelectronic devices, the $\hat{\varepsilon}$ and $\hat{\mu}$ tensors become scalar quantities. The time domain derivative $\partial / \partial t$ appears explicitly only in problems of optical pulse propagation. However, any pulse can be decomposed into a series of harmonic waves, each characterized by a fixed frequency ω. In this case all field vectors have an exponential time dependence given by the factor $\exp(\mathrm{i}\omega t)$, so that the operator $\partial / \partial t$ reduces to a simple multiplication with $\mathrm{i}\omega$. Maxwell's equations for harmonic wave fields in an isotropic medium then become

$$\begin{aligned} &\nabla \times \boldsymbol{E} = -\mathrm{i}\omega\mu\boldsymbol{H}, \\ &\nabla \times \boldsymbol{H} = \mathrm{i}\omega\varepsilon\boldsymbol{E}, \\ &\nabla(\mu\boldsymbol{H}) = 0, \\ &\nabla(\varepsilon\boldsymbol{E}) = 0. \end{aligned} \tag{1.2}$$

The system of equations (1.2) which relates now only the $\boldsymbol{E}$ and $\boldsymbol{H}$ fields can be transformed by using simple operator transformations in two independent equations for $\boldsymbol{E}$ and $\boldsymbol{H}$ which describe the propagation of the electric and magnetic field vectors in inhomogeneous and isotropic media:

$$\begin{aligned} &\nabla^2\boldsymbol{E} + (\nabla\mu / \mu) \times \nabla \times \boldsymbol{E} + \nabla(\boldsymbol{E}\nabla\varepsilon / \varepsilon) + \omega^2\varepsilon\mu\boldsymbol{E} = 0, \\ &\nabla^2\boldsymbol{H} + (\nabla\varepsilon / \varepsilon) \times \nabla \times \boldsymbol{H} + \nabla(\boldsymbol{H}\nabla\mu / \mu) + \omega^2\varepsilon\mu\boldsymbol{H} = 0. \end{aligned} \tag{1.3}$$

In a homogenous medium for which $\varepsilon(\boldsymbol{r}) = \mu(\boldsymbol{r}) =$ const. the above equations reduce to the equations of a harmonic oscillator (Helmholtz equation): $\nabla^2\boldsymbol{F} + \omega^2\varepsilon\mu\boldsymbol{F} = 0$, $\boldsymbol{F} = \boldsymbol{E}, \boldsymbol{H}$. These resemble the equation describing the propagation of the electromagnetic field in the vacuum: $\nabla^2\boldsymbol{F} + k_0^2\boldsymbol{F} = 0$ with the only difference that the wavevector $\boldsymbol{k}_0 = \hat{\boldsymbol{s}}\omega / c$ should be replaced by $n\boldsymbol{k}_0$ where the refractive index n is defined as $n^2 = \varepsilon\mu / \varepsilon_0\mu_0 = c^2\varepsilon\mu$. $\hat{\boldsymbol{s}}$ denotes the unit vector along the direction of propagation and $\varepsilon_0 = 10^7 / 4\pi c^2$ F/m, $\mu_0 = 4\pi 10^{-7}$ H/m are the electric permittivity and magnetic permeability in vacuum, respectively, with $c = 2.998 \cdot 10^8$ m/s the velocity of light.

The system of equations (1.3) is generally difficult to solve. However, in most dielectric waveguides the parameters ε and μ (and implicitly n) have constant values along a direction defined by the unit vector $\hat{z}$ which may or may not coincide with the direction of light propagation. When ε and μ are constant along the direction of light propagation, the solution of the system of equations (1.3) is found by decomposing the total electric and magnetic fields into modes; otherwise one can use the matrix method to find the solution of (1.3). These methods will be briefly discussed in Sects. 1.3 and 1.2, respectively. In both cases, due to the translational invariance of waveguide properties along the z direction, the electric and magnetic fields can be separated as

$$\begin{aligned} \boldsymbol{E}(\boldsymbol{r}) &= \boldsymbol{e}(\boldsymbol{r}_{\mathrm{t}})\exp(\mathrm{i}\beta z), \\ \boldsymbol{H}(\boldsymbol{r}) &= \boldsymbol{h}(\boldsymbol{r}_{\mathrm{t}})\exp(\mathrm{i}\beta z), \end{aligned} \tag{1.4}$$

where β is the propagation constant along the z direction and $\boldsymbol{r}_{\mathrm{t}}$ is the coordinate vector transverse to the z axis. Although in a waveguide the complete solutions of Maxwell's equations are $\boldsymbol{E}(\boldsymbol{r},t) = \boldsymbol{E}(\boldsymbol{r})\exp(\mathrm{i}\omega t)$ and $\boldsymbol{H}(\boldsymbol{r},t) = \boldsymbol{H}(\boldsymbol{r})\exp(\mathrm{i}\omega t)$, with the spatially varying parts given by (1.4), only their real parts, $\mathrm{Re}(\boldsymbol{E}(\boldsymbol{r},t))$ and $\mathrm{Re}(\boldsymbol{H}(\boldsymbol{r},t))$, have physical meaning. With the exception of the cases where temporal averages of products of harmonic functions are involved, the form (1.4) is used to describe the spatially varying parts of the fields. These temporal averages can however be expressed directly in terms of the spatially varying components of the fields by

$$\overline{\boldsymbol{F}(\boldsymbol{r},t)\boldsymbol{G}(\boldsymbol{r},t)} = \mathrm{Re}\left(\overline{\boldsymbol{F}(\boldsymbol{r})}\ \overline{\boldsymbol{G}^{*}(\boldsymbol{r})}\right)/2. \tag{1.5}$$

In orthogonal coordinates, employed in studying planar or channel waveguides, $\boldsymbol{r} = (x,y,z)$, $\boldsymbol{r}_{\mathrm{t}} = (x,y)$ while in polar cylindrical coordinates, used for optical fibers, $\boldsymbol{r} = (r,\phi,z)$, $\boldsymbol{r}_{\mathrm{t}} = (r,\phi)$.

The constant of propagation β can be positive or negative. In this book we adopt the convention that a positive β describes an electromagnetic wave propagating along the positive z direction while a negative value of β indicates that the electromagnetic field propagates in the opposite, negative z direction.

Moreover, $\boldsymbol{e}$ and $\boldsymbol{h}$ which are in general complex quantities, can be decomposed into transverse and longitudinal parts with respect to $\hat{z}$:

$$\begin{aligned} \boldsymbol{e}(\boldsymbol{r}_{\mathrm{t}}) &= \boldsymbol{e}_{\mathrm{t}}(\boldsymbol{r}_{\mathrm{t}}) + \hat{z}\mathrm{e}_{\mathrm{z}}(\boldsymbol{r}_{\mathrm{t}}), \\ \boldsymbol{h}(\boldsymbol{r}_{\mathrm{t}}) &= \boldsymbol{h}_{\mathrm{t}}(\boldsymbol{r}_{\mathrm{t}}) + \hat{z}h_{\mathrm{z}}(\boldsymbol{r}_{\mathrm{t}}). \end{aligned} \tag{1.6}$$

According to the symmetry properties of the electric and magnetic fields at the inversion of the propagation direction, these fields transforms as

$$\begin{aligned} e(r_t) &= e_t(r_t) - \hat{z}e_z(r_t), \\ h(r_t) &= -h_t(r_t) + \hat{z}h_z(r_t), \end{aligned} \tag{1.7}$$

when $\hat{z}$ is replaced with $-\hat{z}$.

1.1.2 Relations Between the Transverse and Longitudinal Components of the Electromagnetic Field in a Translationally Invariant Medium

It can be shown that the transverse and longitudinal components of the electromagnetic field are not independent, but can be related through a set of formulae derived by introducing (1.6) into Maxwell's equations (1.2). The result is:

$$\begin{aligned} h_t &= -\hat{z} \times (\beta e_t - i\nabla_t e_z) / \omega\mu, \\ e_t &= \hat{z} \times (\beta h_t - i\nabla_t h_z) / \omega\varepsilon, \\ h_z &= i\hat{z} \cdot \nabla_t \times e_t / \omega\mu = -i(\nabla_t h_t + h_t \cdot \nabla_t \ln \mu) / \beta, \\ e_z &= i\hat{z} \cdot \nabla_t \times h_t / \omega\varepsilon = -i(\nabla_t e_t + e_t \cdot \nabla_t \ln \varepsilon) / \beta, \end{aligned} \tag{1.8}$$

where ∇_t is the transverse part of the gradient operator $\nabla = \nabla_t + \hat{z}\partial / \partial z$. Equations (1.8) hold for both orthogonal and polar transverse coordinates. In nonabsorbing waveguides (with no propagating loss) ε and μ, as well as n, have real values, while for absorbing waveguides they are complex quantities. For nonabsorbing waveguides (1.7) is consistent with a particular choice of the e and h components, such that the transverse components are real and the longitudinal ones imaginary or vice versa. Such a choice, as for example e_t and h_t real and e_z and h_z imaginary, gives more insight into the physical interpretation.

By eliminating h_t and e_t from the first equations in (1.8), the following relations can be obtained between the transverse and longitudinal components of the electromagnetic field in a translationally invariant medium:

$$\begin{aligned} e_t &= -i(\beta\nabla_t e_z + \omega\mu\hat{z} \times \nabla_t h_z) / (\omega^2\varepsilon\mu - \beta^2), \\ h_t &= -i(\beta\nabla_t h_z - \omega\varepsilon\hat{z} \times \nabla_t h_z) / (\omega^2\varepsilon\mu - \beta^2). \end{aligned} \tag{1.9}$$

The relations derived between the transverse and longitudinal field components are important because they point out that it is not necessary to solve for the components of both e and h in order to obtain the complete solution of Maxwell's equations. The computation of only one field is sufficient for the calculation of the remaining three field vectors (if use is made also of the constitutive equations).

The last two equations in (1.8) have been derived directly from Maxwell's equations (1.2). They could have been derived also from the system of equations (1.3) since it is equivalent to (1.2). However, (1.3) gives us additional information regarding the coupling between the transverse and longitudinal field vectors. Namely by introducing (1.6) into (1.3) it follows that:

$$\begin{aligned} \left(\nabla_t^2 + \omega^2\varepsilon\mu - \beta^2\right)\boldsymbol{h} &= -\left(\nabla_t \boldsymbol{h}_t + \mathrm{i}\beta h_z\right)\cdot\nabla_t \ln\mu - \left(\nabla_t \times \boldsymbol{h} + \mathrm{i}\beta\hat{z}\times\boldsymbol{h}_t\right)\times\nabla_t \ln\varepsilon, \\ \left(\nabla_t^2 + \omega^2\varepsilon\mu - \beta^2\right)\boldsymbol{e} &= -\left(\nabla_t \boldsymbol{e}_t + \mathrm{i}\beta e_z\right)\cdot\nabla_t \ln\varepsilon - \left(\nabla_t \times \boldsymbol{e} + \mathrm{i}\beta\hat{z}\times\boldsymbol{e}_t\right)\times\nabla_t \ln\mu. \end{aligned} \tag{1.10}$$

The above result expresses the fact that the terms containing $\nabla_t \ln\varepsilon$ and $\nabla_t \ln\mu$ couple the different field components. In their absence all field components would independently be solutions of the harmonic oscillator type equations in the left-hand side of (1.10). The terms containing $\nabla_t \ln\varepsilon$ and $\nabla_t \ln\mu$ describe the polarization phenomena due to the waveguide structure. Even in a waveguide with a step refractive index profile these terms do not vanish everywhere; they are different from zero at the interfaces between regions with different refractive indices.

1.2 Matrix Method for Electromagnetic Field Propagation in a Stratified Medium

The simplest method of finding the solution of the electromagnetic field which propagates in a stratified medium is the matrix method. As mentioned above, it is applicable when the direction of the field propagation does not coincide with the direction along which the parameters ε and μ are constant.

Let us assume that our stratified medium is formed from a series of N alternating dielectric layers with different ε and μ values. As before, the direction along which the dielectric constants are invariant is denoted by z, x is the direction perpendicular to the dielectric layers (stratification direction) and y is chosen such that the directions x, y, z form a right handed orthogonal system of coordinates (see Fig. 1.1). If the electromagnetic field, which we will suppose for the moment to be transverse electric (TE) (with $\boldsymbol{e}$ perpendicularly polarized with respect to the propagation direction), is obliquely incident – in the xz plane – on the stratified medium, Maxwell's equations with $\boldsymbol{E}(x,y,z) = \hat{y}E_y(x,y,z)$ are:

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