1 Introduction

In this introductory chapter we will try to define computational photonics and to position it within a broad field of photonics. We will briefly summarize several subfields of photonics (with the main emphasis on optical fibre communication) to indicate potential possibilities where computational photonics can significantly contribute by reducing cost of designing new devices and speeding up their development.

1.1 What is photonics?

We start our discussion from a broader perspective by articulating what photonics is, what the current activities are and where one can get the most recent information.

Photonics is the field which involves electromagnetic energy, such as light, where the fundamental object is a photon. In some sense, photonics is parallel to electronics which involves electrons. Photonics is often referred to as optoelectronics, or as electro-optics to indicate that both fields have a lot in common. In fact, there is a lot of interplay of photonics and electronics. For example, a laser is driven by electricity to produce light or to modulate that light to transmit data.

Photonics applications use the photon in a similar way to that which electronic applications use the electron. However, there are several advantages of optical transmission of data over electrical. Furthermore, photons do not interact between themselves (which is both good and bad), so electromagnetic beams can pass through each other without interacting and/or causing interference.

Even with the telecommunication ‘bubble’ which happened some ten years ago, the subfield of photonics, namely optical fibre communication, is still a very important segment of photonics activities. As an example, a single optical fibre has the capacity to carry about 3 million telephone calls simultaneously. But, due to a crisis around 2000, many new applications of photonics have emerged or got noticed. Bio-photonics or medical photonics are amongst the most important ones.

Before we try to define computational photonics, let us concentrate for a moment on what photonics is at the time of writing (Winter, 2011). In the following paragraphs, we cite some information from the relevant conferences.

Some of the well-established conferences which summarize research and applications in a more traditional approach to photonics, and also dictate new directions are: Photonics West, held every January in California (here is the 2011 information [1]); Photonics East, taking place in the eastern part of the USA in the Fall; Optical Fibre Conference (OFC) taking place in March every year [2].

A new conference, the Photonics Global Conference (PGC), is a biennial event held since 2008 [3]. The aim of this conference is to foster interactions among broad disciplines in photonics with concentration on emerging directions. Symposia and Special Sessions for 2011 are summarized below:

- Symposia: 1. Optofluidics and Biophotonics. 2. Fibre-Based Devices and Applications. 3. Green Photonics. 4. High-Power Lasers and Their Industrial Applications. 5. Metamaterials and Plasmonics. 6. Nanophotonics. 7. Optical Communications and Networks.
- Special Sessions: 1. Quantum Communications. 2. Photonics Crystal Fibres and Their Applications. 3. Photonics Applications of Carbon Nanotube and Graphene. 4. Terahertz Technology. 5. Diffuse Optical Imaging.

By looking at the discussed topics, one can get some sense about current activities in photonics.

1.2 What is computational photonics?

Computational photonics is a branch of physics which uses numerical methods to study properties and propagation of light in waveguiding structures. (Here, light is used in a broad sense as a replacement for electromagnetic waves.) Within this field, an important part is played by studies of the behaviour of light and light-matter interactions using analytical and computational models. This emerging field of computational science is playing a critically important role in designing new generations of integrated optics modules, long haul transmission and telecommunication systems.

Generally, computational photonics is understood as the ‘replacement’ of the experimental method, where one is performing all the relevant ‘experiments’ on computer. Obviously, such an approach reduces development cost and speeds-up development of new products.

We will attempt to cover some of those developments. The field is, however, so broad that it is impossible to review all of its activities. Naturally, selection of the topics reflects author’s expertise.

As a separate topic in photonics, one selects integrated photonics where the concentration is on waveguides, simulations of waveguide modes and photonic structures [4]. The central role is played there by a beam-propagation method which will be discussed later in the book.

1.2.1 Methods of computational photonics. Computational electromagnetics

According to Joannopoulos *et al.* [5], in a broad sense there are three categories of problems in computational photonics: frequency-domain eigensolvers, frequency-domain solvers and time-domain simulations. Those problems are extensively discussed in many sources including [5], also [6] and [7].

A recent general article by Gallagher [8] gives an introduction to the main algorithms used in photonic computer aided design (CAD) modelling along with discussion of their strengths and weaknesses. The main algorithms are:

- BPM – Beam Propagation Method
- EME – Eigenmode Expansion Methods
- FDTD – Finite Difference Time Domain.

The above methods are compared against speed, memory usage, numerical aperture, the refractive index contrasts in the device, polarization, losses, reflections and nonlinearity. The author's conclusion is that none of the discussed algorithms are universally perfect for all applications.

We finish this section by indicating that application of computational electromagnetics goes well beyond photonics, see the discussion by Jin [6]. In fact it has an extremely wide range of applications which goes from the analysis of electromagnetic wave scattering by various objects, antenna analysis and design, modelling and simulation of microwave devices, to numerical analysis of electromagnetic interference and electromagnetic compatibility.

1.2.2 Computational nano-photonics

This subfield has emerged only in recent years. As the dimensions of photonics devices shrink, it plays an increasingly important role. Nanostructures are generally considered as having sizes in the order of the wavelength of light. At those wavelengths, multiple scattering and near-field effects have a profound influence on the propagation of light and light-matter interaction. In turn, this leads to novel regimes for basic research as well as novel applications in various disciplines.

For instance, the modified dispersion relation of photonic crystals and photonic crystal fibres leads to novel nonlinear wave propagation effects such as giant soliton shifts and supercontinuum generation with applications in telecommunication, metrology and medical diagnostics. Owing to the complex nature of wave interference and interaction processes, experimental studies rely heavily on theoretical guidance both for the design of such systems as well as for the interpretation of measurements. In almost all cases, a quantitative theoretical description of such systems has to be based on advanced computational techniques that solve the corresponding numerically very large linear, nonlinear or coupled partial differential equations.

University research on photonic crystal structures applied to novel components in optical communication, boomed since it has become possible to create structures on the nanometre scale. Nanotechnology offers a potential for more efficient integrated optical circuitry at lower cost – from passive elements like filters and equalizers to active functions such as optical switching, interconnects and even novel lasers. In addition, the technology can provide new functionality and reduce overall optical communication cost thanks to smaller devices, higher bandwidth and low loss device characteristics that eliminate the need for amplification. The ultimate goal is to create three-dimensional photonic structures that may lead to progressively optical and one day all-optical computing.

A very recent overview on modelling in photonics, including discussion of important computational methods, was written by Obayya [9].

1.2.3 Overview of commercial software for photonics

An outstanding progress in photonics has been to a great extent possible due to the availability of reliable software. Some of the main commercial players are listed below:

1. At the time of writing, Optiwave (www.optiwave.com) provides comprehensive engineering design tools which benefit photonic, bio-photonic and system design engineers with a comprehensive design environment. Current Optiwave products include two groups: system and amplifier design, and component design.
   For system and amplifier design they offer two packages:
   - OptiSystem – suite for design of amplifier and optical communication systems.
   - OptiSPICE – the first optoelectronic circuit design software.

   For component design, they have the following products:
   - OptiBPM, based on the beam propagation method (BPM), offers design of complex optical waveguides which perform guiding, coupling, switching, splitting, multiplexing and demultiplexing of optical signals in photonic devices.
   - OptiFDTD, which is based on the finite-difference time-domain (FDTD) algorithm with second-order numerical accuracy and the most advanced boundary condition, namely uniaxial perfectly matched layer. Solutions for both electric and magnetic fields in temporal and spatial domain are obtained using the full-vector differential form of Maxwell's equations.
   - OptiFiber, which uses numerical mode solvers and other models specialized to fibres for calculating dispersion, losses, birefringence and polarization mode dispersion (PMD).
   - OptiGrating, which uses the coupled mode theory to model the light and enable analysis and synthesis of gratings.
2. RSoft (www.rsoftdesign.com) product family includes:
   - Component Design Suite to analyse complex photonic devices and components through industry-leading computer-aided design,
   - System Simulation to determine the performance of optical telecom and datacom links through comprehensive simulation techniques and component models, and
   - Network Modeling for cost-effective deployment of DWDM and SONET technologies while designing and optimizing an optical network.
3. Photon Design (www.photond.com)
   They offer several products for both passive and active component design, such as FIMMWAVE and CrystalWave.
   FIMMWAVE is a generic full-vectorial mode finder for waveguide structures. It combines methods based on semi-analytical techniques with other more numerical methods such as finite difference or finite element.
   FIMMWAVE comes with a range of user-friendly visual tools for designing waveguides, each optimized for a different geometry: rectangular geometries often

encountered in epitaxially grown integrated optics, circular geometries for the design of fibre waveguides, and more general geometries to cover, e.g. diffused waveguides or other unusual structures.

CrystalWave is a design environment for the layout and design of integrated optics components optimized for the design of photonic crystal structures. It is based on both FDTD and finite-element frequency-domain (FEFD) simulators and includes a mask file generator optimized for planar photonic crystal structures.

4. CST MICROWAVE STUDIO (www.cst.com/Content/Products/MWS/Overview.aspx) is a specialist tool for the 3D electromagnetic simulation of high frequency components. It enables the fast and accurate analysis of high frequency devices such as antennas, filters, couplers, planar and multi-layer structures.

There are several web resources devoted to photonics software and numerical modelling in photonics. We mention the following: Optical Waveguides: Numerical Modeling Website [10], Photonics resources page [11] and Photonics software [12].

1.3 Optical fibre communication

In this section we will outline the important role played by photonics in the communication over an optical fibre. Other sub-fields will be summarized in due course.

1.3.1 Short story of optical fibre communication

Light was used as a mean for communication probably since the origin of our civilization. Its modern applications in telecommunication, as developed in the twentieth century, can be traced to two main facts:

- availability of good optical fibre, and
- compact and reliable light sources.

Later in this section, we will discuss main developments in some detail. We start with a short history of communication with the emphasis on light communication. A recent popular history of fibre optics written for a broad audience was published by Hecht [13]. As an introductory work we recommend simple introduction to fundamentals of digital communications by Bateman [14].

1.3.2 Short history of communication

After discovery of electromagnetic waves due to work by Marconi, Tesla and many others, the radio was created operating in the 0.5–2 MHz frequency range with a bandwidth of 15 kHz. With the appearance of television which required bandwidth of about 6 MHz, the carrier frequencies moved to around 100 MHz. During the Second World War the

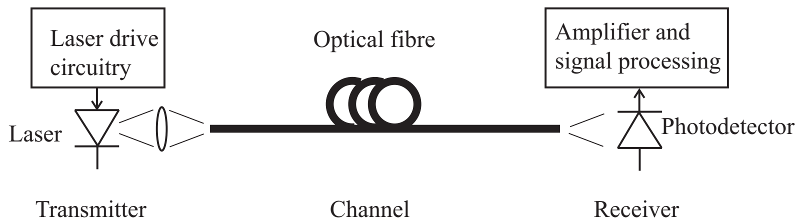

Fig. 1.1 Block diagram of a fibre system.

invention of radar pushed the frequencies to the microwave region (around GHz). Those frequencies (range of 2.4–5 GHz) are now actively used by cell phones as well as wireless links.

The big step toward higher frequencies was made possible in the 1960s with the invention of laser. The first one operated at the 694 nm wavelength. This corresponds to carrier frequency of approximately 5×10^{14} Hz (5×10^5 GHz $=$ 500 THz). Utilization of only 1% of that frequency represents a signal channel of about 5 THz which can accommodate approximately 10^6 analogue video channels, each with 6 MHz bandwidth or 10^9 telephone calls at 5 kHz per call.

A typical communication channel which links two points, point-to-point link (as an example, see Fig. 1.1 for a generic fibre optics link), consists of an optical transmitter which is usually a semiconductor laser diode, an optical fibre intended to carry light beam and a receiver. A semiconductor laser diode can be directly modulated or an external modulator is used which produces modulated light beam which propagates in the optical fibre. Information is imposed into optical pulses. Then the light is input into the optical fibre where it propagates over some distance, and then it is converted into a signal which a human can understand.

All of those elements should operate efficiently at the corresponding carrier's frequencies (or wavelengths). In the 1960s only one element was in place: a transmitter (laser). The other two elements were nonexistent.

The next main step was proposed in 1966 by Charles Kao and George Hockham [15] who demonstrated the first silica-based optical fibre with sufficiently low enough propagation loss to enable its use as a communication medium. Soon, silica-based optical fibre became the preferred means of transmission in both long- and short-haul telecommunication networks. An all-optical network has the potential for a much higher data rate than combined electrical and optical networks and allows simultaneous transmission of multiple signals along one optical fibre link.

Below, we summarize selected developments of the early history of long-distance communication systems (after Hecht [13] and Einarsson [16]):

- TAT-1 (1956) First transatlantic telephone system contained two separate coaxial cables, one for each direction of transmission. The repeaters (based on vacuum tubes) were spliced into the cables at spacing of 70 km. Capacity of the transmission was 36 two-way voices.

- TAT-6 (1976) Capacity of 4200 two-way telephone channels. Repeaters (based on transistors) were separated at a distance of 9.4 km.
- TAT-7 (1983) System similar to TAT-6.
- TAT-8 (1988) First intercontinental optical fibre system between USA and Europe.
- HAW-4 (1988) System installed between USA and Hawaii; similar to TAT-8.
- TCP-3 Extension of HAW-4 to Japan and Guam.
- TAT-12 (1996) First transatlantic system in service with optical amplifiers.

A typical optical fibre used in TAT-8 system supported single-mode transmission [16]. It had outer diameter of 125 μm and core diameter of 8.3 μm. It operated at 1.3 μm wavelength. Digital information was transmitted at 295.6 Mbits. The repeaters which regenerated optical signals were spaced 46 km apart.

Some of the main developments that took place in relation to development of fibre communication are summarized below (compiled using information from Ref. [13]):

- October 1956: L. E. Curtiss and C. W. Peters described plastic-clad fibre at Optical Society of America meeting in Lake Placid, New York.
- Autumn 1965: C. K. Kao concludes that the fundamental limit on glass transparency is below 20 dB km^{-1} which would be practical for communication.
- Summer 1970: R. D. Maurer, D. Keck and P. Schultz from Corning Glass Works, USA make a single-mode fibre with loss of 16 dB km^{-1} at 633 nm by doping titanium into fibre core.
- April 22, 1977: General Telephone and Electronics. First live telephone traffic through fibre optics, at 6 Mbits^{-1} in Long Beach, CA.
- 1981: British Telecom transmits 140 Mbits s^{-1} through 49 km of single-mode fibre at 1.3 μm wavelength.
- Late 1981: Canada begins trial of fibre optics to homes in Elie, Manitoba.
- 1988: L. Mollenauer of Bell Labs demonstrates soliton transmission through 4000 km of single-mode fibre.
- February 1991: M. Nakazawa, NTT Japan sends soliton signals through a million km of fibre.
- 1994: World Wide Web grows from 500 to 10 000 servers.
- 1996: Introduction of a commercial wavelength-division multiplexing (WDM) system.
- July 2000: Peak of telecom bubble. JDS Uniphase announces plans to merge with SDL Inc. in stock deal valued at $41 billion.
- 2001: NEC Corporation and Alcatel transmitted 10 terabits per second through a single fibre [17].
- December 2001: Failure of TAT-8 submarine cable.

The capacity of optical fibre communication systems grew very fast. Comparison with Moore's law for computers which states that computer power doubles every 18 months, indicates that fibre capacity grows faster [18]. In 1980, a typical fibre could carry about 45 Mb s^{-1}; in 2002 a single fibre was able to transmit more than 3.5 Tb s^{-1} of data. Over those 22 years the computational power of computers has increased 26 000 times whereas the fibre capacity increased 110 000 times over the same period of time.

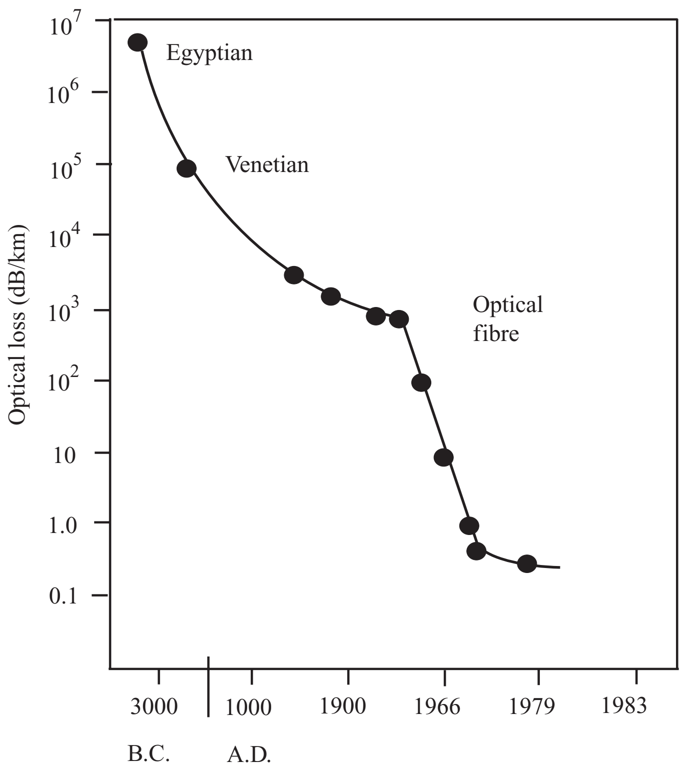

Fig. 1.2 Historical reduction of loss as a function of time from ancient times to the present. Copyright 1989 IEEE. Reprinted, with permission from S. R. Nagel, *IEEE Communications Magazine*, **25**, 33 (1987).

1.3.3 Development of optical fibre

Glass is the principal material used to fabricate optical fibre. To be useful as a transmission medium it has to be extremely clean and uniform. In Fig. 1.2 we illustrated the history of reduction losses in glass as a function of time (after [19]). To make practical use of glass as a medium used to send light, an important element, and in fact the very first challenge was to develop glass so pure that 1% of light entering at one end would be retained at the other end of a 1 km-thick block of glass. In terms of attenuation this 1% corresponds to about 20 decibels per kilometre (20 dB km^{-1}).

In 1966 Kao and Hockhman [15] suggested that the high loss in glass was due to impurities and was not the intrinsic property of glass. In fact, Kao suggested to use optical fibre as a transmission medium.

Kao's ideas were made possible in 1970 with the fabrication of low-loss glass fibre by the research group from Corning Glass Works [20]. That work established a potential of optical communications for providing a high bandwidth and long distance data transmission network. Corning Glass Works were the first to produce an optical glass with a transmission loss of 20 dB km^{-1}, which was thought to be the threshold value to permit efficient optical communication.

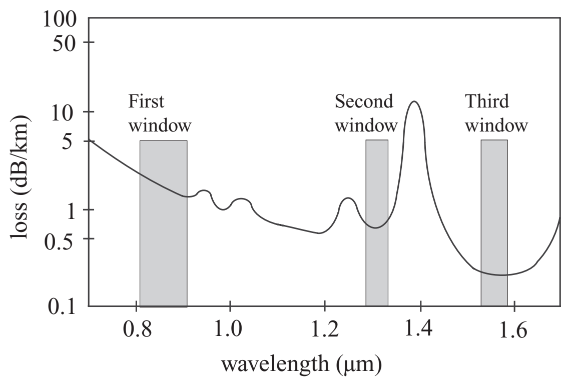

Fig. 1.3 Spectral loss of a typical low-loss optical fibre. Adapted from [22] with permission from the Institution of Engineering and Technology.

Before the Corning work, around 1966, the power loss for the best available glass was about 1000 dB km^{-1} which implies a 50% power loss in a distance of about 3 m [21]. Today, most optical fibres in use are so-called single-mode fibre able to maintain single mode of operation (see Chapter 5 for the relevant definitions). Commercially available fibres have losses of about 0.2 dB km^{-1} at the wavelength of 1550 nm and are capable of transmitting data at 2–10 Gbit s^{-1}.

The measured spectral loss of a typical low-loss optical fibre is shown in Fig. 1.3 [22]. The measured fibre had 9.4 μm core diameter and a 0.0028 refractive index difference between the core and cladding. Peaks were found at about 0.94, 1.24 and 1.39 μm. They were caused by OH vibrational absorption. The rise of the loss from 1.7 μm is mainly attributed to the intrinsic infrared absorption of the glass.

The locations of the first, second and third communications windows are also shown. The most common wavelengths used for optical communication span between 0.83–1.55 μm. Early technologies used the 0.8–0.9 μm wavelength band (referred to as the first window) mostly because optical sources and photodetectors were available at these wavelengths. Second telecommunication window, centered at around 1.3 μm, corresponds to zero dispersion of fibre. Dispersion is a consequence of the velocity propagation being different for different wavelengths of light. As a result, when pulse travels through a dispersive media it tends to spread out in time, the effect which ultimately limits speed of digital transmission. The third window, centered at around 1.55 μm, corresponds to the lowest loss. At that wavelength, the glass losses approach minimum of about 0.15 dB km^{-1}.

For the sake of comparison, the loss of about 0.2 dB km^{-1} corresponds to 50% power loss after propagation distance of about 15 km.

1.3.4 Comparison with electrical transmission

Historically, copper was a traditional medium used to transmit information by electrical means. Its data handling capacity is, however, limited. Only around 1970, after the fabrication of relatively low-loss optical fibre, it started to be used in an increasing scale. From practical perspective, the choice between copper or glass is based on several factors.

In general, optical fibre is chosen for systems which are used for longer distances and higher bandwidths, whereas electrical transmission is preferred in short distances and relatively low bandwidth applications. The main advantages of electrical transmission are associated with:

- relatively low cost of transmitters and receivers
- ability to carry electrical signals and also electrical power
- for not too large quantities, relatively low cost of materials
- simplicity of connecting electrical wires.

However, it has to be realized that optical fibre is much lighter than copper. For example, 700 km of telecommunication copper cable weighs 20 tonnes, whereas optical fibre cable of the same length weighs only around 7 kg [23].

The main advantages of optical fibre are:

- fibre cables experience effectively no crosstalk
- they are immune to electromagnetic interference
- lighter weight
- no electromagnetical radiation
- small cable size.

1.3.5 Governing standards

In order for various manufacturers to be able to develop components that function compatibly in fibre optic communication systems, a number of standards have been developed and published by the International Telecommunications Union (ITU) [24]. Other standards, produced by a variety of standards organizations, specify performance criteria for fibre, transmitters and receivers to be used together in conforming systems.

These and related standards are covered in a recent publication [25]. It is the work of over 25 world-renowned contributors and editors. It provides a reference to over a hundred standards and industry technical specifications for optical networks at all levels: from components to networking systems through global networks, as well as coverage of networks management and services.

The ITU has specified six transmission bands for fibre optic transmission [18]:

1. the O-band (original band) – 1260–1310 nm,
2. the E-band (extended band) – 1360–1460 nm,
3. the S-band (short band) – 1460–1530 nm,
4. the C-band (conventional band) – 1530–1565 nm,
5. the L-band (long band) – 1565–1625 nm,
6. the U-band (ultra band) – 1625–1675 nm.

A seventh band, not defined by the ITU, runs around 850 nm and is used in private networks.