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INTRODUCTION TO INTEGRATED PHOTONICS

Introduction

The term "integrated photonics" refers to the fabrication and integration of several photonic components on a common planar substrate. These components include beam splitters, gratings, couplers, polarisers, interferometers, sources and detectors, among others. In turn, these can then be used as building blocks to fabricate more complex planar devices which can perform a wide range of functions with applications in optical communication systems, CATV, instrumentation and sensors. The setting-up of integrated photonic technology can be considered as the confluence of several photonic disciplines (dealing with the control of light by electrons and vice versa) with waveguide technology. In fact, optical waveguides are the key element of integrated photonic devices that perform not only guiding, but also coupling, switching, splitting, multiplexing and demultiplexing of optical signals. In this chapter we will introduce the main characteristics of integrated photonic technology, showing relevant aspects concerning material and fabrication technologies. Also, we will briefly describe some basic components present in integrated photonic devices, emphasising the differences in their design compared to conventional optics. Some examples of integrated photonic devices (passive, functional, active and non-linear) are given at the end of the chapter to show the elegant solution that this technology proposes for the development of advanced optical devices.

1.1 Integrated Photonics

Optics can be defined as the branch of physical science which deals with the generation and propagation of light and its interaction with matter. Light, the main subject of optics, is electromagnetic (EM) radiation in the wavelength range extending from the vacuum ultraviolet (UV) at about 50 nanometers to the far infrared (IR) at 1 mm. In spite of being a very ancient science, already studied by the founder of the School of Alexandria, Euclid, in his *Optics* (280 BC), during the last quarter of the past century, the science of optics has suffered a spectacular renaissance, due to various key developments. The first revolutionary event in modern optics was, no doubt, the invention of the laser by T.H. Maiman in 1960 at Hughes Research Laboratories in Malibu [1], which allowed the availability of coherent light sources with exceptional properties, such as high spatial and temporal coherence and very high brightness. A second major step forward came with the development of semiconductor optical devices for the generation and detection of light, which permitted very efficient and compact opto-electronic devices. The last push was given by the introduction of new fabrication techniques for obtaining very cheap optical fibres, with very low propagation losses, close to the theoretical limits (Figure 1.1).

As a result of these new developments and associated with other technologies, such as electronics, new disciplines have appeared connected with optics: electro-optics, opto-electronics, quantum electronics, waveguide technology, etc. Thus, classical optics, initially dealing with lenses, mirrors, filters, etc., has been forced to describe a new family of much more complex devices such as lasers, semiconductor detectors, light modulators, etc. The operation of these devices must be described in terms of optics as well as of electronics, giving birth to a mixed discipline called *photonics*. This new discipline emphasises the increasing role that electronics play in optical devices, and also the necessity of treating light in terms of photons rather than waves, in particular in terms of matter–light interactions (optical amplifiers, lasers, semiconductor devices, etc.). If electronics can be considered as the discipline that describes the flow of electrons, the term "photonics" deals with the control of photons. Nevertheless, these two disciplines clearly overlap in many cases, because photons can control the flux of electrons, in the case of detectors, for example, and electrons themselves can determine the properties of light propagation, as in the case of semiconductor lasers or electro-optic modulators.

The emergence of novel photonic devices, as well as resulting in the important connection between optics and electronics, has given rise to other sub-disciplines within photonics. These new areas include electro-optics, opto-electronics, quantum optics, quantum electronics and non-linear optics, among others. *Electro-optics* deals with the study of optical devices in which the electrical interaction plays a relevant role in controlling the flow of light, such as electro-optic modulators, or certain types of lasers. *Acousto-optics* is the science and technology concerned with optical devices controlled by acoustic waves, driven by piezo-electric transducers. Systems which involve light

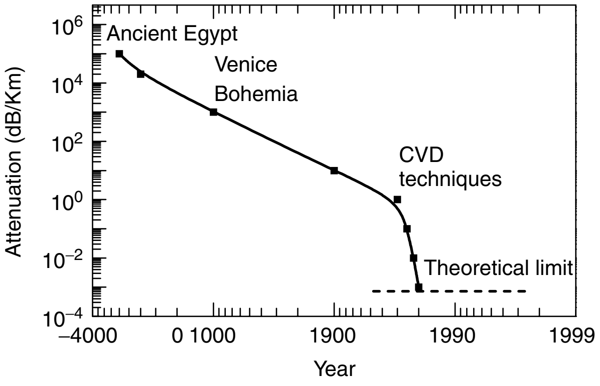

Figure 1.1 Evolution of the attenuation in silica glasses. In the 1980s the dramatic drop in the attenuation coincides with the boom of the optical fibre systems, thanks to the implementation of new fabrication techniques

but are mainly electronic fall under *opto-electronics*; these systems are in most cases semiconductor devices, such as light-emitting diodes (LEDs), semiconductor lasers and semiconductor-based detectors (photodiodes). The term *quantum electronics* is used in connection with devices and systems that are based on the interaction of light and matter, such as optical amplifiers and wave-mixing. The quantum nature of light and its coherence properties are studied in *quantum optics*, and the processes that involve non-linear responses of the optical media are covered by the discipline called *non-linear optics*. Finally, some applied disciplines emerging from these areas include *optical communications*, *image* and *display systems*, *optical computing*, *optical sensing*, etc. In particular, the term *waveguide technology* is used to describe devices and systems widely used in optical communications as well as in optical computing, optical processing and optical sensors.

A clear example of an emergent branch of optics that combines some of the above disciplines is the field of *integrated optics*, or more precisely, *integrated photonics*. We consider integrated photonics to be constituted by the combining of waveguide technology (guided optics) with other disciplines, such as electro-optics, acousto-optics, non-linear optics and opto-electronics (Figure 1.2). The basic idea behind integrated photonics is the use of photons instead of electrons, creating integrated optical circuits similar to those in conventional electronics. The term "integrated optics", first proposed in 1960 by S.E. Miller [2], was introduced to emphasise the similarity between planar optical circuits technology and the well-established integrated micro-electronic circuits. The solution proposed by Miller was to fabricate integrated optical circuits through a process in which various elements, passive as well as active, were integrated in a single substrate, combining and interconnecting them via small optical transmission lines called waveguides. Clearly, integrating multiple optical functions in a single photonic device is a key step towards lowering the costs of advanced optical systems, including optical communication networks.

The optical elements present in integrated photonic devices should include basic components for the generation, focusing, splitting, junction, coupling, isolation, polarisation control, switching, modulation, filtering and light detection, ideally all of them

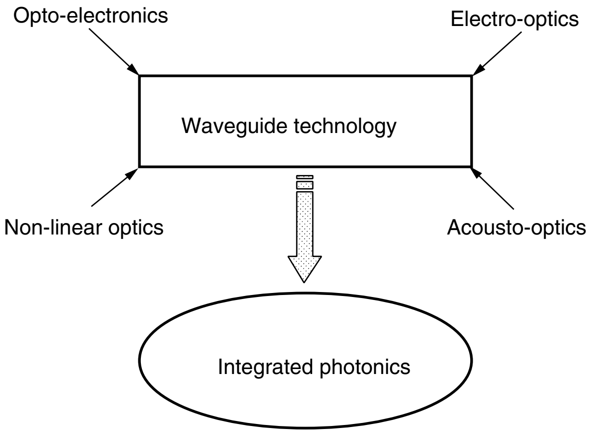

Figure 1.2 Confluence of various disciplines into integrated photonics

being integrated in a single *optical chip*. Channel waveguides are used for the interconnection of the various optical elements. The main goal pursued by integrated photonics is therefore the miniaturisation of optical systems, similar to the way in which integrated electronic circuits have miniaturised electronic devices, and this is possible thanks to the small wavelength of the light, which permits the fabrication of circuits and compact photonic devices with sizes of the order of microns. The integration of multiple functions within a planar optical structure can be achieved by means of planar lithographic production [3]. Although lithographic fabrication of photonic devices requires materials different from those used in microelectronics, the processes are basically the same, and the techniques well established from 40 years of semiconductor production are fully applicable. Indeed, a lithographic system for fabricating photonic components uses virtually the same set of tools as in electronics: exposure tools, masks, photoresists, and all the pattern transfer process from mask to resist and then to device.

1.2 Brief History of Integrated Photonics

For 30 years after the invention of the transistor, the processing and transmission of information were based on electronics that used semiconductor devices for controlling the electron flux. But at the beginning of the 1980s, electronics was slowly supplemented by and even replaced by optics, and photons substituted for electrons as information carriers. Nowadays, photonic and opto-electronic devices based on integrated photonic circuits have grown in such a way that they not only clearly dominate long-distance communications through optical fibres, but have also opened up new fields of application, such as sensor devices, and are also beginning to penetrate in the own field of the information processing technology. In fact, the actual opto-electronic devices may be merely a transition to a future of all-optical computation and communication systems.

The history of integrated photonics is analogous to that of other related technologies: discovery, fast evolution of the devices, and a long waiting time for applications [4]. The first optical waveguides, fabricated at the end of the 1960s, were bidimensional devices on planar substrates. In the mid-1970s the successful operation of tridimensional waveguides was demonstrated in a wide variety of materials, from glasses to crystals and semiconductors. For the fabrication of functional devices in waveguide geometries, lithium niobate ($LiNbO_3$) was rapidly recognised as one of the most promising alternatives. The waveguide fabrication in $LiNbO_3$ via titanium in-diffusion was demonstrated at the AT&T Bell Laboratory, and gave rise to the development of channel waveguides with very low losses in a material that possesses valuable electro-optic and acousto-optic effects. In the mid-1980s the viability of waveguide devices based on $LiNbO_3$, such as integrated intensity modulators of up to 40 GHz, and with integration levels of up to 50 switches in a single photonic chip had already been demonstrated in laboratory experiments. A few years later, the standard packaging required in telecommunication systems was obtained, and so the devices were ready to enter the market. The rapid boom of monomode optical fibre systems which started in the 1980s was the perfect niche market for these advanced integrated photonic devices that were waiting in the research laboratories. Indeed, the demand for increased transmission capacity (bandwidth) calls urgently for new integrated photonic chips that permit the control and processing of such huge data transfer, in particular with the introduction of technology to transmit light in multiple wavelengths (WDM, wavelength division multiplexing).

Because of the parallel development of other materials, both dielectrics such as polymers, glasses or silica on silicon (SiO_2/Si), and semiconductors such as indium phosphide (InP), gallium arsenide (GaAs) or even silicon (Si), a wide variety of novel and advanced integrated photonic devices was ready to emerge on the market. During the last two decades of the twentieth century we have moved from the development of the new concept of integrated optical devices to a huge demand for such novel devices to implement sophisticated functions, mainly in the optical communication technology market. In fact, at the beginning of the twenty-first century the data transfer created by computer-based business processes and by Internet applications is growing exponentially, which translates into a demand for increasing transmission capacity at lower cost, which can only be met by increased use of optical fibre and associated advanced photonic technologies (Figure 1.3). Today fibres are typically used to transmit bit-rates up to 10 Gbit/s, which is, however, far below the intrinsic bandwidth of an optical fibre. Wavelength Division Multiplexing (WDM) (the transmission of several signals through a single fibre using several wavelengths) paves the way to transmit information over an optical fibre in a much more efficient way, by combining several 10 Gbit/s signals on a single fibre. Today there are commercial WDM systems available with bit-rates in the range of 40 to 400 Gbit/s, obtained by combining a large number of 2.5 and 10 Gbit/s signal, and using up to 32 different wavelengths. The next frontier in data transfer capacity points to the Terabit transmission, which can be achieved by using Time Domain Multiplexing (TDM), an obvious multiplexing technique for digital signals. An equivalent of TDM in the optical domain (OTDM) is also being developed with the purpose of reaching much higher bit-rates which will require the generation and transmission of very short pulses, in the order of picoseconds, and digital processing in the optical domain. Clearly, all these technologies will require highly advanced optical components, and integrated photonic devices based on planar lightwave circuits are the right choice to meet the high performance levels required, which allow the integration of multiple functions in a single substrate (Table 1.1).

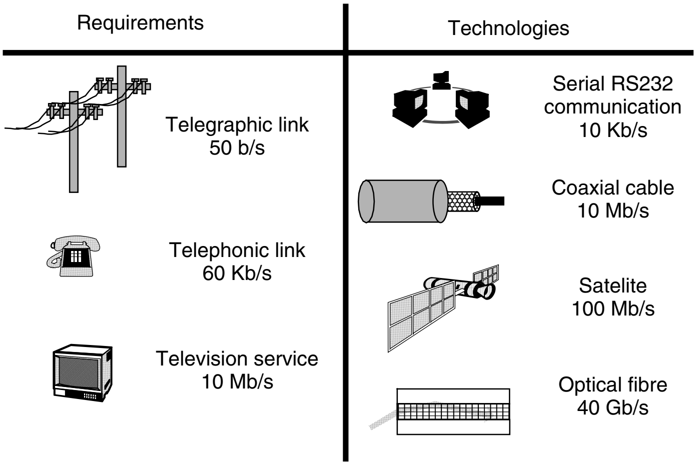

Figure 1.3 Requirements for data transfer and available technologies

Table 1.1 Integrated optics market in 2001 by material type [5]

Material	%
Lithium niobate	30
Indium phosphide	22
Gallium arsenide	20
Silica on silicon	11
Polymer	5
Silicon	3
Other	9
TOTAL	100

1.3 Characteristics of the Integrated Photonic Components

The basic idea behind the use of photons rather than electrons to create integrated photonic circuits is the high frequency of light (200 THz), which allows a very large bandwidth for transporting and managing a huge amount of information. The replacement of electronic by photonic means is forced by fundamental physical reasons that limit the information transmission rate using purely electronic means: as the frequency of an electrical signal propagating through a conductor increases, the impedance of the conductor also increases, thus the propagation characteristics of the electrical cable become less favourable. That is the reason why electrical signals with frequencies above 10 MHz must be carried by specially designed conductors, called coaxial cables, in order to minimise the effect of a high attenuation. Figure 1.4 shows the attenuation in a typical coaxial cable as a function of the frequency. It can be seen that for high transmission rates (~100 MHz), the attenuation is so high (~5 dB/Km) that communications based on electrical signals propagating on coaxial cables can be used in applications where the typical distances are tens of metres (buildings), but they are

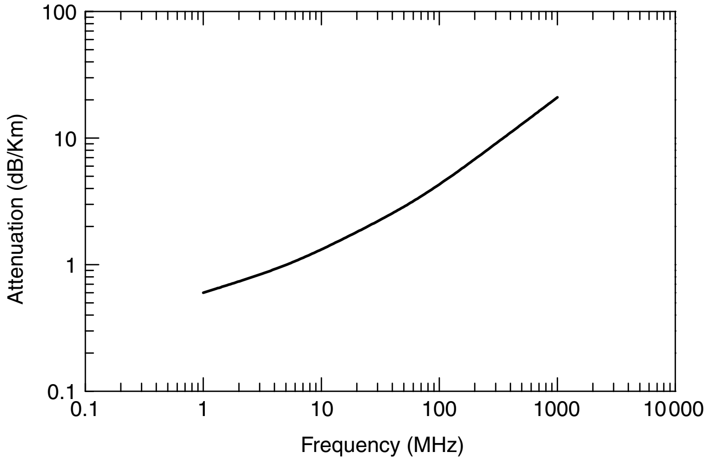

Figure 1.4 Attenuation of the electrical signal in a coaxial cable as a function of the modulation frequency

useless for distances greater than several kilometres (links between cities). In contrast, optical signals propagate through non-conducting dielectric media, operating in the wavelength range where the materials are highly transparent. For most optical materials used in optical communications and photonic devices, this transparent window falls in the visible and near-infrared range of the electromagnetic spectrum, which corresponds to light frequency in the range 150–800 THz, 10^6 times the frequency used in electrical transmission!

Integrated photonic devices based on integrated optical circuits take advantage of the relatively short wavelength of the light in this range (0.5–2 μm), which allows the fabrication of miniature components using channel waveguides the size of microns. The technology required to fabricate planar lightwave circuit components of such dimensions is therefore common in the well-established Micro-electronic technology, using the tools and techniques of the semiconductor industry.

The basic concept in optical integrated circuits is the same as that which operates in optical fibres: the confinement of light. A medium that possesses a certain refractive index, surrounded by media with lower refractive indices, can act as a light trap, where the rays cannot escape from the structure due to the phenomena of total internal reflection at the interfaces. This effect confines light within high refractive index media, and can be used to fabricate optical waveguides that transport light from point to point, whether long distances (optical fibres) or in optical circuits (integrated photonic chips). Figure 1.5 shows the basic structures for the most common waveguide geometries. In a planar waveguide (Figure 1.5a) light is trapped by total internal reflection in a film (dashed region), and therefore the film must have a refractive index greater than the refractive indices corresponding to the upper and lower media. These are usually referred to as the *cover* and the *substrate*, respectively, and the film is called the *core*, because that is where most of the optical energy is concentrated.

In a channel waveguide the light propagates within a rectangular channel (the dashed region in Figure 1.5b) which is embedded in a planar substrate. To confine light within the channel it is necessary for the channel to have a refractive index greater than that of the substrate, and of course, greater than the refractive index of the upper medium, which is usually air. This type of waveguide is the best choice for fabricating integrated photonic devices. Because the substrate is planar, the technology associated with integrated optical circuits is also called *planar lightwave circuits* (PLC).

Finally, Figure 1.5c shows the geometry of an optical fibre, which can be considered as a cylindrical channel waveguide. The central region of the optical fibre or core is surrounded by a material called *cladding*. Of course, the core must have a higher

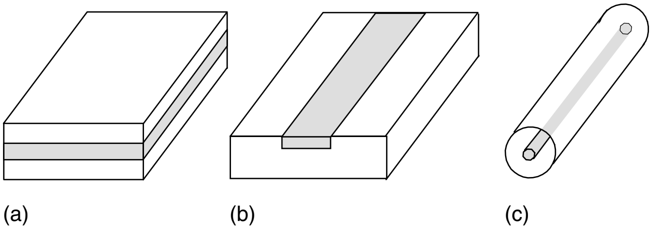

Figure 1.5 Basic waveguide geometries: (a) planar waveguide; (b) channel waveguide; (c) optical fibre

refractive index than the cladding in order to trap light within the structure after total internal reflection.

In both channel waveguides and optical fibres the confinement of optical radiation takes place in two dimensions, in contrast to planar waveguides where there is only light confinement in a single direction. This fact allows light in planar waveguides to diffract in the plane of the film, whereas in the case of channel waveguides and fibres diffraction is avoided, forcing the light propagation to occur only along the structure's main axis.

Three generations can be distinguished in the evolution of optical systems, from conventional optical systems to integrated optical circuits (Table 1.2). The first generation concerns *conventional optical* systems, where the optical components with sizes of the order of centimetres were set on optical benches typically with dimensions of metres, while the optical beams had diameters of the order of several millimetres. A second generation in the evolution of optical systems can be called *micro-optics*. Its main characteristic is the use of miniature optical components such as light emitting diodes, diode lasers, multi-mode fibres, etc. These components are clearly a transition towards the devices used nowadays in modern communication systems based on optical fibres. Nevertheless, although the characteristics of micro-optic systems are satisfactory, there are problems with the alignment and coupling between the components because of their small size (of the order of millimetres). Furthermore, because of the critical alignment, the various optical components are not packed together, making the optical system unstable. The last generation in optical systems concerns integrated photonics, and is based on optical circuits and components integrated in a single substrate. This, as well as the small size of the optical components, is the key factor for the success of integrated photonic systems. This technology, with unique features with respect to previous generations, possesses important advantages in terms of choice of materials, design, fabrication and performance characteristics. Some of the special features of systems based on integrated photonic technology are the following:

1. *Functionality based on electromagnetic optics*. The key elements in an integrated optical device are monomode channel waveguides with width and depth typically of the order of microns, where the optical radiation propagates in a single mode. In this way, while the optical systems of the first and second generation can be adequately

Table 1.2 Evolution of the optical systems technology and relevant characteristics [6]

	First generation	Second generation	Third generation
Technology	Conventional optics	Micro-optics	Integrated photonics
Typical components	Mirrors, prisms, lenses, gas lasers	LED, LD, tiny lenses, multi-mode fibres	Monomode channel waveguides, LD, monomode fibres
Alignment	Necessary	Necessary (hard)	Unnecessary
Propagation	Beam	Beams in multi-mode waveguides	Monomode waveguides (μm)
Control electrode size	1 cm	1 mm	1 μm
Device size	1 m^2	10 cm^2	1 cm^2 (on a 1 mm thick substrate)

Note: LED: light emitting diode; LD: laser diode.

treated by ray optics because of the wide diameters of the optical beams (compared to the wavelength of the light), integrated optical devices must be analysed considering the propagating light as electromagnetic waves.

2. *Stable alignment*. A key factor in the good performance of an optical system is the adjustment and alignment of the various optical components, which is critical and difficult to achieve for conventional optical systems. In contrast, in integrated photonic devices, once the optical chip has been fabricated, the alignment problem is avoided and stability is assured. Furthermore, the device is stable against vibrations or thermal changes. This characteristic, which is the most relevant feature in integrated photonic devices, is assured because all the optical elements are integrated in a single substrate.
3. *Easy control of the guided modes*. Because the waveguides are monomode, it is easier to control the optical radiation flux through the electro-optic, acousto-optic, thermo-optic or magneto-optic effects, or even by the light itself via non-linear interactions. If the waveguides were multi-mode, this control by external fields would be much more complicated, because of the different propagation characteristics of each modal field.
4. *Low voltage control*. For devices based on light control via the electro-optic effect, the short width of the channel waveguides allows one to drastically reduce the distance between the control electrodes. This implies that the voltage required to obtain a certain electric field amplitude can be considerably reduced. For example, while the typical voltage for electro-optic control in conventional optical systems is of the order of several KV, in integrated optic devices the voltage required is only a few volts.
5. *Faster operation*. The small size of the control electrodes in an electro-optic integrated photonic device implies low capacitance, and this allows for a faster switching speed and higher modulation bandwidth. Typical modulations of 40 Gbit/s are easily achieved using lithium niobate, polymers or InP-based devices.
6. *Effective acousto-optic interactions*. Since the field distributions of surface acoustic waves (SAW) are located within a distance of a few wavelengths beneath the substrate surface (tens of microns), the SAW and the optical waveguide modes overlap strongly, giving rise to efficient acoustooptic interactions. Thus, using SAW generated by piezotransducers, high performance integrated optical devices based on acoustooptic effect can be developed.
7. *High optical power density*. Compared with conventional optical beams, the optical power density in a monomode channel waveguide is very high, due to the small cross-sectional area of the guide. This is of special relevance in the performance of devices requiring high radiation intensity, such as frequency converters (via non-linear effects) or even optical amplifiers and lasers. These devices are therefore very efficient when designed and fabricated with integrated photonic technology.
8. *Compact and low weight*. The use of a single substrate with an area of several millimetres squared for integrating different photonic components makes the optical chip very compact and very light weight.
9. *Low cost*. The development of integration techniques makes mass production possible via lithographic techniques and mask replication; also, the planar technology reduces the quantity of material necessary to fabricate the photonic devices. These

aspects are the basis of a low cost device and thus an easy introduction into the market.

1.4 Integrated Photonics Technology

The technology and fabrication methods associated with integrated optical circuits and components are very varied, in addition, they depend on the substrate material with which the optical device is fabricated. The methods most widely used in the definition of optical circuits over a substrate are diffusion techniques (such as titanium diffusion in lithium niobate) and deposition techniques (such as chemical vapour deposition used for silica). Since the lateral dimensions of the optical circuits are only a few microns, the fabrication technology needs photolithographic processes. In the case of diffusion techniques it is possible to use photolithographic masks to define open channels through which the diffused material enters the substrate, or, alternatively, one can deposit the previously patterned material to be diffused directly onto the substrate. For waveguides fabricated by deposition techniques the lateral definition of the optical circuits is usually carried out by means of etching after the deposition of the material onto the whole substrate surface.

Optical integration can expand in two directions: serial integration and parallel integration. In serial integration for optical communication devices the different elements of the optical chip are consecutively interconnected: laser and driver, modulator and driver electronics, and detector and receiver electronics. In parallel integration, the chip is built by bars of amplifiers, bars of detectors and wavelength (de)multiplexors. Also, a combination of these two architectures should incorporate optical cross-connects and add-drop modules. The highest level of integration (whether serial or parallel) is achieved in monolithic integration, where all the optical elements including light sources, light control, electronics and detectors are incorporated in a single substrate. The most promising materials to achieve full monolithic integration are semiconductor materials, in particular GaAs and InP. In hybrid integration technology, the optical chip fabricated on a single substrate controls the optical signals, while additional elements such as lasers or detectors are built on different substrates and are directly attached to the integrated photonic device or interconnected by optical fibres. Examples of hybrid technologies include dielectric substrates, such as glasses, silica or ferro-electric crystals. The case of silica on silicon can be considered as quasi-hybrid integration, in the sense that optical components, electronics and detector can be implemented in a single substrate, but not the light source.

All integrated photonic devices require input/output optical signals carried by optical fibres. Indeed, one of the most difficult tasks in packaging an integrated optical device is attaching the fibres to the chip waveguides, known as fibre pigtails. The fibre alignment is typically 0.1 micron or less for low power loss, where the optical chip surfaces should be carefully polished at odd angles to eliminate back reflection from the interface. This alignment must be maintained during the attachment and also through subsequent thermal transitions as well as in shock and vibration-prone environments while the device is operating.

Lithography replicates a prototype from chip to chip or from substrate to substrate. Although a lithographic system for fabricating photonic devices uses the same tools as in semiconductor electronics, there are some important differences. First, while in electronics, bends and interconnections affect the maximum data rates, in photonic circuits the major impact is on optical power throughput. Second, while electrons strongly interact with each other, photons can exist even in the same circuit without interacting. As a consequence, integrated circuits in electronics usually have an overall square geometry, with multiple layers to enable the cross-over of electrical signals, while integrated optical chips tend to have a single layer and an elongated geometry with unidirectional flow to minimise bending of the optical path.

Although there is a great number of lithographically processable materials that can be used to fabricate optical waveguides, only a few of them have shown the required characteristics to develop integrated optical devices. These include a wide range of glasses, crystals and semiconductors (Table 1.3). In particular, the substrates most commonly used are glasses, lithium niobate, silica on silicon, III-V semiconductor compounds and polymers. Each type of material has its own advantages and disadvantages, and the choice of a specific substrate depends on the particular application of the photonic device. Nowadays there exists a great variety of devices based on each of these materials.

The glass-based integrated optical devices have the great advantage of the low cost of the starting material and the fabrication technique, mainly performed by an ionic exchange process [7]. The method used for producing waveguides in glass substrates

Table 1.3 Materials technology for integrated photonic devices

Substrate	Material properties	Waveguide technology	Advantages	Demonstrated devices
Multi-components Glasses	Low price Rare earths incorporation	Ionic exchange	Easy and cheap fabrication Low losses	Passive devices Amplifiers
SiO_xN_y:SiO_2:Si TiO_2/SiO_2/Si	Cheap and versatile fabrication	Thermal oxidation CVD, FHD, ECR, Sol-gel	Versatility Microelectronic technology	Passive devices TO switches AWG
Lithium niobate	Electro-optic Acousto-optic Non-linear Bi-refringent	Metallic diffusion Protonic exchange	Easy control of light Anisotropic	Switches Modulators Couplers WDM and DWDM
III-V compounds (InP, GaAs)	Electro-optic Light source Light detection Electronics	Epitaxy (MBE, LPE, CVD, MOCVD)	High level of integration	Modulators Amplifiers Lasers AWG
Polymers	Electro-optics Thermo-optics Non linear	Spin coating Dip Coating	High versatility Wide range of physical properties	Chemical and biological sensors TO switches EO Modulators

Notes: CVD: chemical vapour deposition; FHD: flame hydrolysis deposition; ECR: electron cyclotron resonance; MBE: molecular beam epitaxy; LPE: liquid phase epitaxy; MOCVD: metal-organic chemical vapour deposition; TO: thermo-optic; AWG: arrayed waveguide grating; WDM: wavelength division multiplexing; DWDM: dense WDM; EO: electro-optic.

is the exchange of alkali ions from the glass matrix (usually Na^+ ions) for monovalent cations such as K^+, Ag^+, Cs^+ or Tl^+, immersing the glass substrate in a molten salt that contains some of these ions at temperatures in the range 200–500°C, depending on the type of glass and the particular salt. For defining the optical circuits, a stopping mask is deposited onto the substrate, in such a way that the ionic exchange takes place only in the channels opened in the mask. This mask is removed after the exchange process. The refractive index increase due to the ionic exchange depends both on the glass composition and on the exchanged ions, and typically varies in the range 0.01 to 0.1. Since the glasses are amorphous materials, they do not present physical properties useful for the direct control of light, and therefore they are used mainly for the fabrication of passive devices.

One of the materials most widely used in the fabrication of integrated optical devices is lithium niobate ($LiNbO_3$) [8]. This is due to several characteristics of this crystalline material. In the first place, $LiNbO_3$ presents very interesting physical properties: in particular, it has valuable acousto-optic, electro-optic and piezo-electric effects. These properties allow the fabrication of functional devices such as phase modulators, switches, directional couplers, multiplexors, etc. Besides being a birefringent material, $LiNbO_3$ shows high non-linear optical coefficients, and these two properties permit very efficient frequency conversion, such as second harmonic generation and optical parametric oscillation. Furthermore, several techniques for waveguide fabrication in $LiNbO_3$ are now well established, including Ti or Zn metallic diffusion, protonic exchange, or even ion implantation. The resulting waveguides have very low losses, typically in the range of 0.01–0.2 dB/cm. Integrated optical circuits technology based on $LiNbO_3$ substrates is now very well established, and a great variety of devices based on this technology, mainly in the field of optical communications, are now commercially available.

The main advantage of silica over silicon-based photonic waveguides is the low price and the good optical quality of the silicon substrates, besides being a well-known material with a long tradition, and the experience developed from micro-electronic technology. The first step in waveguide fabrication using silicon substrates is the deposition of a silicon dioxide layer a few microns thick, which can also be obtained by direct oxidation of the silicon at high temperature. This layer has a double purpose: to provide a low index region for allowing light confinement, and also to move away the highly absorbing silicon substrate. For this reason this layer is called a *buffer* layer. The waveguide core is formed by further deposition of a high index oxynitride layer, usually via the chemical vapour deposition method (CVD) or the flame hydrolysis deposition (FHD) method [9]. The refractive index of the oxynitride core, SiO_xN_y, can be continuously varied in the range 1.45–2.1 by controlling the relative concentration of SiO_2 and Si_3N_4 compounds during the deposition. As the SiO_2 buffer layer has a refractive index of 1.45, a very high index contrast between the waveguide core and the surrounding media can be obtained. The most appealing feature of silicon as a substrate in integrated photonics is the possibility of integrating the detector and the associated electronic in a single platform substrate.

Perhaps, second to $LiNbO_3$ the III–V semiconductor compounds (mainly GaAs and InP) are the substrates with greatest impact on integrated optics technology, and are probably the materials with the most promising future in this field [10, 11]. The importance of the III–V compounds in integrated photonics derives from the fact that they offer the possibility of a high level of monolithic integration. Indeed, InP is a very versatile platform that promises large-scale integration of active components (lasers and detectors), passive components, and also electronics. The electronic technology of these semiconductor materials is now well established, and optical waveguide fabrication is quite straightforward by modifying the dopant concentration during the deposition process, Al in the case of GaAs, and Ga or As in the case of InP. The main problem concerning this technology has its roots in the relatively high losses of waveguides made of these materials (>1 dB/cm). Nevertheless, the fabrication technology in InP is rapidly improving, and several integrated photonic devices that show very high performance are now available in the market, such as semiconductor optical amplifiers, arrayed waveguide gratings or high speed modulators.

Among the materials suitable for integrated photonic technology, polymers occupy a special position, due to the fact that they exhibit some very useful physical properties, such as electro-optic, piezo-electric and non-linear effects, with values even higher that those of lithium niobate crystals [12]. Also, the thermo-optic coefficient for polymers is more than ten times higher than the corresponding coefficients for silica. The waveguide fabrication method for polymers starts from a solution of the polymeric material, followed by a deposition by spin coating or dip coating on a substrate. Due to their easy processing, the polymer layers allow for great flexibility when choosing a substrate; they are compatible with very different substrates such as glasses, silicon dioxide, or even silicon and indium phosphide. The choice of a particular polymeric material should take into consideration some important properties such as high transparency, easy processing, and high physical, chemical, mechanical and thermal stability. The main advantage of polymer-based integrated optical devices is their high potential for use in the field of chemical and biological sensors, because the organic groups in the polymeric compound can be designed and tailored to react against a specific medium. Also, due to the large electro-optic coefficient showed by some polymers, high speed and low voltage switches and modulators have been developed for the telecommunication market, offering high performance at low cost.

1.5 Basic Integrated Photonic Components

As in electronics, in integrated photonics there are some basic components common to most of the integrated optical devices. Although in essence all these components basically perform the same functions as their corresponding devices in conventional optics, the operating principles are usually quite different, and thus their design has very little to do with traditional optical components.

Although nowadays a long list of integrated photonic devices has been proposed, modelled and fabricated, and their number is quickly increasing, the basic components remain almost unchanged. Therefore it is possible to describe a short list of such components, basic blocks from which much more complex integrated optical devices can be built. We will now briefly outline some of the most common components, and we will show the dramatic change in design concept of integrated photonic devices compared to conventional optical components performing the same function. The main difference in design comes from the fact that while in conventional optics the operation principle is based on the behaviour of the light considered as plane waves or rays, in integrated optics the modelling and performance of the devices should be treated using the formalism of electromagnetic waves; this is because the size of the beams is of the order of the light's wavelength, typically in the range of microns. In fact, optical propagation in integrated photonic devices is conveyed through optical channels with dimensions of a few micrometres, both in depth and in width. Channel waveguides are defined in a single plane substrate, and other related elements (electrodes, piezoelements, heaters, etc.) are mounted on the same substrate, giving rise to a robust and compact photonic device. Unless otherwise stated, all the basic components that we will now describe will be based on monomode channel waveguides.

All the optical components in integrated photonics are constructed with three building blocks. They are the straight waveguide, the bend waveguide and the power splitter. Using these building blocks, several basic components have been developed to perform basic optical functions. In addition, a particular function can be executed using different elements, whose design may differ substantially. This versatility in optical element conception is one of the special features of integrated photonic technology. Now, we shall discuss several of these basic blocks and optical elements that perform some basic functions common in many integrated optical devices.

- *Interconnect.* This basic element serves to connect optically two points of a photonic chip (Figure 1.6a). The straight channel waveguide (Figure 1.6b), being the simplest structure for guiding light, interconnects different elements which are aligned on the optical chip. It can also act as a spatial filter, maintaining a Gaussian-like mode throughout the chip architecture. In order to interconnect different elements which are not aligned with the optical axis of the chip, a bend waveguide is needed, and therefore a bend waveguide is often called an offset waveguide (Figure 1.6c). These are also used to space channel waveguides at the chip endfaces, so that multiple fibres may be attached to it.
- *Power splitter* 1 × 2. A power splitter 1 × 2 is usually a symmetric element which equally divides power from a straight waveguide between two output waveguides (Figure 1.6d). The simplest version of a power splitter is the Y-branch (Figure 1.6e), which is easy to design and relatively insensitive to fabrication tolerances. Nevertheless, the curvature radii of the two branches, as well as the junction, must be carefully designed in order to avoid power losses. Also, if the two branches are separated by tilted straight waveguides, the tilt angle must be small, typically a few degrees. A different version of a power splitter is the multi-mode interference element (MMI, Figure 1.6f). This name comes from the multi-modal character of the wide waveguide region where the power split takes place. The advantage of this design is the short length of the MMI compared to that of the Y-branch. Although the dimensions of the MMI are not critical, allowing wide tolerances, this element must be designed for a particular wavelength. The two power splitters which have been described are symmetric, and thus 50% of the input power was carried by each output waveguide. Nevertheless, asymmetric splitters can also be designed for specific purposes. In addition, it is possible to fabricate splitters with N output waveguides, and in that case the element is called a 1 × N splitter.
- *Waveguide reflector.* The waveguide reflector performs the task of reflecting back the light in a straight waveguide (Figure 1.6g). The simplest method of performing this task is to put a metallic mirror at the end of the channel waveguide (Figure 1.6h). If one needs the reflection to occurs only for a particular wavelength, a multistack dielectric mirror is used. Another way of building a waveguide reflector is

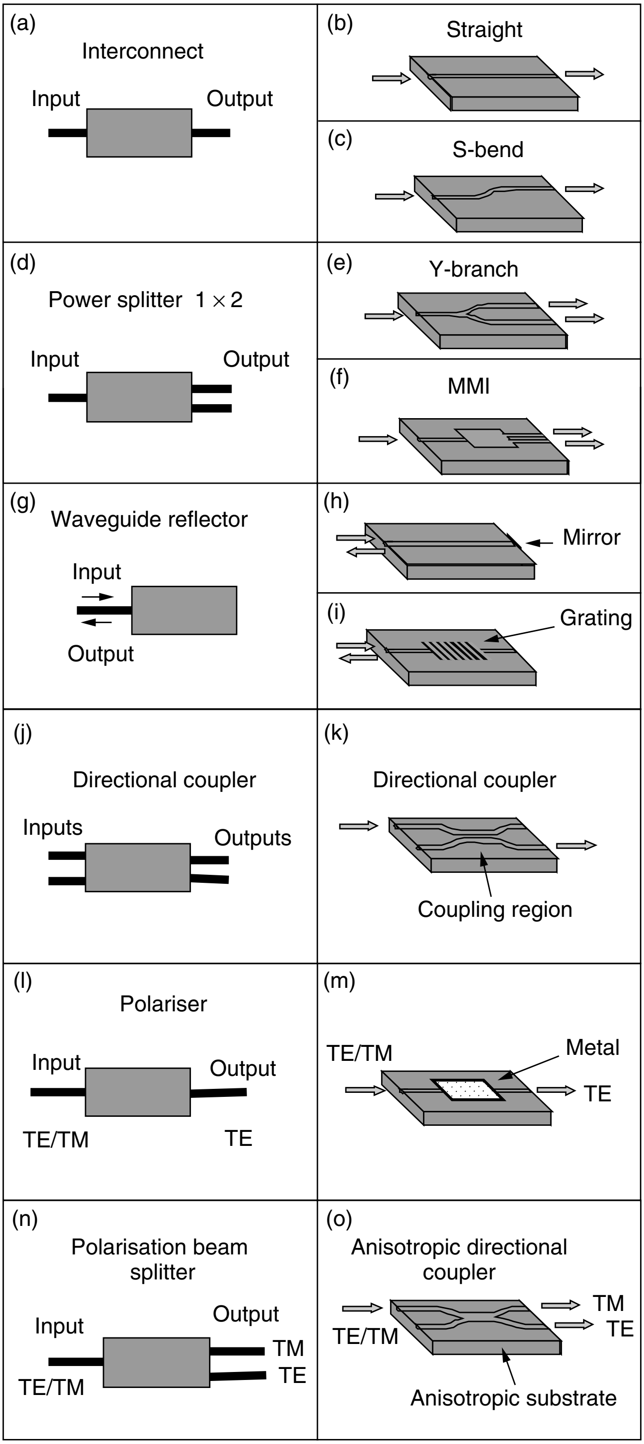

Figure 1.6 Integrated photonics elements

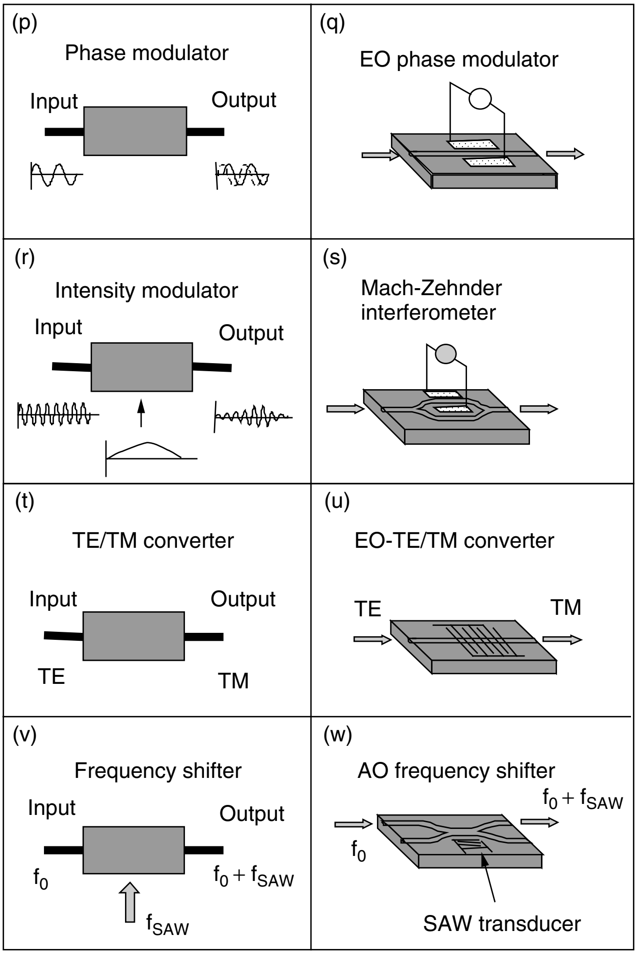

Figure 1.6 (*continued*)

to implement a grating in a region of the straight waveguide (Figure 1.6i). The grating is inherently a wavelength selective element, and thus the grating period must be calculated for the specific working wavelength. The reflection coefficient of the grating depends on the length of the grating region and on the modulation refractive index depth. The wavelength selectivity of the grating is also used for designing waveguide filters working under Bragg condition. Besides this, the grating in integrated photonics can be used as an optical element for performing a wide range of functions such as focusing, deflection, coupling and decoupling light in the waveguide, feedback in an integrated laser, sensors, etc.

- *Directional coupler*. This element has two input ports and two output ports (Figure 1.6j), and is composed of two closely spaced waveguides (Figure 1.6k). The working principle of the coupler is based on the periodical optical power exchange that occurs between two adjacent waveguides through the overlapping of the evanescent waves of the propagating modes. This effect is described by the coupled mode formalism described in Chapter 4. By setting design parameters, including waveguide spacing and coupler length, the ratio of powers between the two output ports may be set during the fabrication process to be between zero and 1.

- *Polariser*. A waveguide polariser allows to pass light having a well defined polarisation character, either TE or TM light, by filtering one of them (Figure 1.6l). The fabrication of a waveguide polariser is as simple as depositing a metallic film onto a waveguide (Figure 1.6m): the light propagating along the waveguide with its electric field perpendicular to the substrate plane (TM mode) is strongly attenuated because of the resonant coupling with the superficial plasmon modes. In this way, at the waveguide output, only light with TE polarisation is present. As the TE mode also suffers some attenuation, the nature of the metal as well as the metallic film length must be carefully chosen in order to obtain a high polarisation ratio, while maintaining a high enough TE light power. An alternative way of obtaining a waveguide polariser is to design a waveguide that supports only TE polarised modes. These are obtained, for example, in lithium niobate waveguides fabricated by the protonic exchange method. In this fabrication process, while the extraordinary index increases, the ordinary index decreases, thus forming a waveguide that supports only extraordinary polarised modes.
- *Polarisation beam splitter*. In some integrated optical devices, it is necessary to divide the input light into its two orthogonal polarisation, TE and TM, in two separate waveguide output ports (Figure 1.6n). Figure 1.6o shows an integrated optical element based on a lithium niobate substrate, which performs this function: the intersecting waveguide operates as a directional coupler whose behaviour depends on the beat between odd-mode light and even-mode light for TE-mode and TM-mode light, respectively [13]. The TE-mode light propagates to the cross-output port and the TM-mode light to the parallel output port. This polarisation selectivity is based on the birefringence of $LiNbO_3$. The length and the width of the intersecting region must be carefully controlled to obtain high extinction ratios of both polarisations, for a chosen wavelength.
- *Phase modulator*. An integrated optical phase modulator performs a controlled shift on the phase of a light beam (Figure 1.6p), and consists of a channel waveguide fabricated on a substrate with the possibility of changing its refractive index by means of an externally applied field (thermal, acoustic, electric, etc.). The most common phase modulator is based on the electro-optic effect: an electric field applied to an electro-optic material, such as $LiNbO_3$, induces a change in its refractive index. If the electric field is applied through a channel waveguide, the change in the refractive index induces a change in the propagation constant of the propagating mode, and therefore the light travelling through that region undergoes a certain phase shift (Figure 1.6q). The geometry of the electrodes and the voltage control depend on the crystal orientation and on the device structure. For high modulation frequency a special electrode configuration is necessary, such as the *travelling wave* configuration or *phase reversal electrodes* configuration.
- *Intensity modulator*. One of the most important functions of an optical chip is the intensity modulation of light at very high frequencies (Figure 1.6r). One of the most simple ways to perform this task is to build an integrated Mach-Zehnder interferometer (MZI) on an electro-optic substrate (Figure 1.6s). The MZI starts with a channel monomode waveguide, and then splits it in two symmetric branches by means of a

Y-branch. After some distance, the two branches becomes parallel. The MZI continues with a symmetric reverse Y-branch, and ends in a straight waveguide. If the MZI is exactly symmetric, the input light splits at the first Y-junction into the two parallel branches, and then recombines constructively into the final straight waveguide. On the contrary, if in one of the interferometer's arms the light suffers a phase shift of 180°, at the end of the second Y-branch the light coming from the two branches will recombine out of phase, and will give rise to destructive interference, with no light at the output. In practice, the phase shift in one arm is carried out via the electro-optic effect, by applying a voltage across the waveguide. By adequately choosing the crystal orientation, polarisation, electrode geometry and applied voltage, a total phase shift of 180° can be obtained for a specific wavelength.

- *TE/TM mode converter*. In a normal situation, TE and TM modes are orthogonal, and then the power transfer between them cannot occur. Nevertheless, TE to TM conversion (Figure 1.6t) can be achieved by using electro-optic substrates, which must have non-zero off-diagonal elements in the electro-optic coefficient matrix. If lithium niobate is used as a substrate, a periodic electrode is required because this crystals is birefringent, and therefore the TE and TM modes have different effective refractive indices (propagation speeds) (Figure 1.6u). By combining phase modulators and a TE/TM converter, a fully integrated polarisation controller can be built.
- *Frequency shifter*. Frequency shifting in integrated optics (Figure 1.6v) can be performed by means of the acousto-optic effect. An acoustic surface wave (SAW) generated by a piezo-electric transducer, creates a Bragg grating in the acousto-optic substrate that interacts with the propagating light in a specially designed region, giving rise to diffracted light that is frequency-shifted by the Doppler effect (Figure 1.6w). This frequency shift corresponds to the frequency of the acoustic wave.

1.6 Some Examples of Integrated Photonics Devices

The optical elements that can be found in an optical chip can be classified according to their function as passive, functional, active and non-linear. A passive optical element has fixed input/output characteristics, which are determined when the photonic component is fabricated. Examples of these are the power splitter, waveguide reflector, directional coupler, polariser, and polarisation beam splitter. Functional optical elements are photonic components which are driven by externally applied fields (for example, electric, acoustic or thermal). The above described phase modulator, intensity modulator, frequency converter and electro-optic TE/TM converter fall into this category. Although some authors call these devices active devices, we will keep the name "active devices" for photonic components that perform functions such as optical amplification and laser oscillation. This choice of nomenclature is due to the fact that they use active impurities such as rare earths embedded in the waveguide structure, to obtain light amplification (or oscillation) via a luminescence process after optical (or electrical) pumping. The integrated optical amplifier and the integrated laser are two examples of active devices. Finally, some integrated optical devices make use of the non-linearity of certain materials to perform frequency doubling or optical parametric oscillation, where the optical chip's function is to generate new frequencies via a non-linear optical process. Since the efficiency of non-linear processes is proportional to the

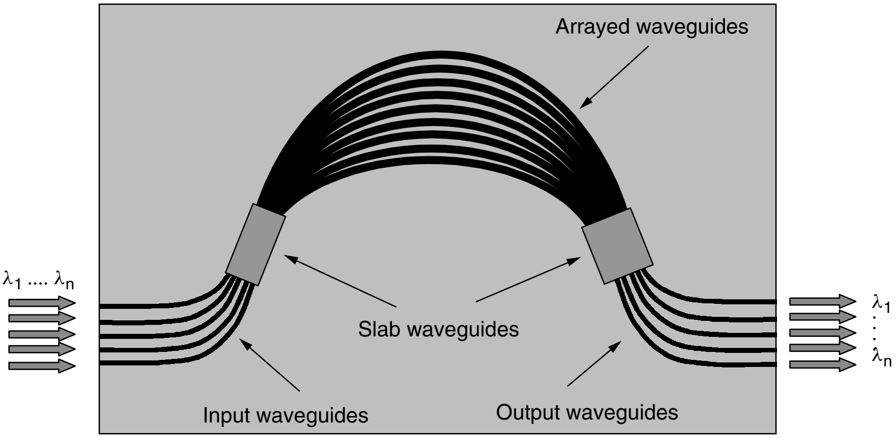

Figure 1.7 The arrayed waveguide grating (AWG) is one example of a passive integrated photonics device, used for dense wavelength demultiplexing

light intensity, these devices yield a very good performance in the integrated photonic version, because of the small transverse area of the waveguide propagating beams.

Figure 1.7 shows an example of a passive integrated photonic device, in which no external signal is needed for its operation. This device is called an arrayed waveguide grating (AWG, PHASAR or waveguide grating router, WGR); its function is to passively multiplex or demultiplex signals of closely spaced wavelengths, and it is used in fibre optical communication systems [14]. Several wavelengths coming through a single fibre enter the AWG via any of its input waveguides. A coupler splits light between many of the curved waveguides which define the AWG. The arrayed waveguides are formed by waveguides having different lengths, and therefore light suffers different phase shift for each curved waveguide. By precisely adjusting the phase shift from each curved waveguide with respect to all the others, an interferometric pattern is set up that results in light of different wavelengths being focused at different spatial location on an output arc. Since the AWG distribute signals according to their wavelength, each individual waveguide output corresponds to a specific wavelength, thereby acting as a demultiplexor.

An example of a functional device, which also combines some passive elements is the acousto-optic tuneable filter (AOTF) (Figure 1.8) [15]. This integrated optical device requires an external radio-frequency (RF) control signal to selectively separate one or more wavelength signals (drop signals). This device is fabricated with $LiNbO_3$ and is composed of a piezo-transducer, a thin film acoustic waveguide and two polarisation beam splitters. The multi-wavelength input signals propagate over the optical waveguide and are divided into their perpendicular components (TE/TM) by the first polarisation beam splitter (PBS). Surface acoustic waves (SAW), generated by applying an RF signal to the transducer, travel through the SAW guide and cause a periodic modulation of the optical waveguide's refractive index. The periodic refractive index change induces TE–TM or TM–TE conversion for the drop wavelength only. The drop wavelength corresponds to the applied RF frequency and becomes perpendicular to the incident light. The second PBS is then used to separate the drop wavelength from the incident light. By using several RF signals simultaneously, it is even possible to drop several wavelengths.

Several substrate materials compatible with integrated photonic technology are also suitable to incorporate optically active rare earth ions, which makes it possible to fabricate active integrated optical devices [16]. Figure 1.9 shows the arrangement of an integrated optical amplifier based on Erbium and Ytterbium ions. It basically consists of a straight waveguide, which has rare earth ions incorporated to it, an undoped waveguide and a directional coupler. The input pumping at 980 nm is injected into the undoped waveguide, and the coupler transfers the pump energy to the doped straight waveguide. Via several radiative, non-radiative and energy transfer mechanisms which takes place on the Erbium and Ytterbium ions, the feeble input signal at 1533 nm

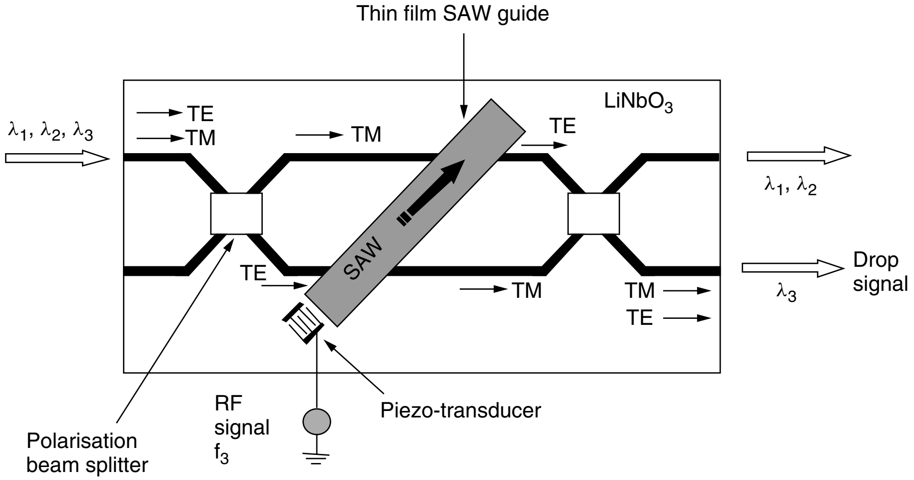

Figure 1.8 The integrated acousto-optic tuneable filter uses polarisation conversion, via the interaction between the light guide modes and the surface acoustic waves generated by a piezo-electric transducer, to spatially separate any of the selected input wavelengths (drop signals). Since the device is externally controlled by the RF frequency applied to the transducer, this is one example of a functional integrated photonic device

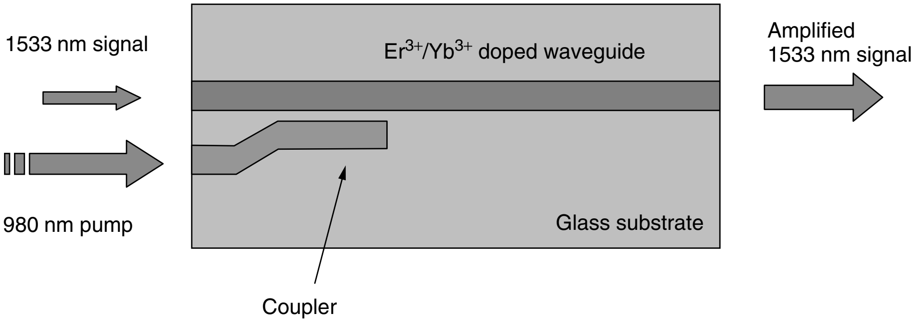

Figure 1.9 The integrated optical amplifier based on rare earths is one example of active integrated photonic chips

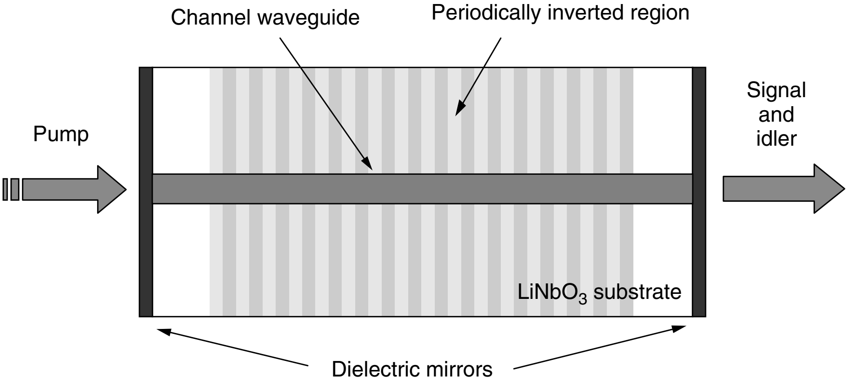

Figure 1.10 The high optical non-linear coefficients of LiNbO$_3$ crystals make this substrate suitable for developing non-linear integrated photonic devices, such as the optical parametric oscillator presented here. Also, for high efficiency conversion, it is necessary to fabricate a periodically poled region along the waveguide structure

is amplified as it propagates along the straight waveguide. If a couple of dielectric mirrors are attached at the two waveguide ends, the amplified signal can oscillate, and therefore an integrated laser can be obtained. The end mirrors can also be replaced by integrated gratings, acting as a true wavelength-selective reflector.

Integrated optical parametric oscillators (OPOs) in ferro-electric crystals have been identified as the most useful tuneable non-linear frequency converters with many applications, mainly in environmental sensing and process monitoring. These non-linear integrated photonic devices are based on ferro-electric materials showing high values of second order nonlinearities, and are capable of obtaining a periodic inversion of the ferroelectric domains. Figure 1.10 presents the design of an optical parametric oscillator in its integrated optical version: a straight channel waveguide is fabricated on a z-cut LiNbO$_3$ substrate, where a periodically poled region has been patterned perpendicular to the waveguide [17]. The two dielectric mirrors, directly attached to the waveguide ends, allow parametric oscillation at the signal and idler frequencies, which are created from the input pump via non-linear optical interactions. For efficient optical parametric oscillation the crystal orientation must be adequately chosen, as well as the periodicity of the ferro-electric domain structure.

1.7 Structure of the Book

The rest of the book has been divided into four chapters and some appendices. This first chapter aimed to present an overview of integrated photonic technology, stressing the radical conceptual change of photonic chips compared to traditional optical systems. Although several technical terms have been used throughout this chapter (modes, coupling, TE/TM conversion, etc.) without a rigorous definition, they will be further studied in subsequent chapters. Chapter 2 gives the basic EM theory necessary for developing and understanding light behaviour in waveguide structures, starting from Maxwell's equations. The theory of optical waveguides is introduced in Chapter 3.

For a correct description of light in waveguide structures having dimensions comparable to its wavelength, the light must be contemplated as EM waves. Therefore, the waveguide theory discussed in Chapter 3 is based on the EM theory of light, where the important concept of optical waveguide mode is introduced. In this chapter we start analysing the planar waveguide structure, where the most relevant concepts are explained. Also, once one-dimensional waveguides are studied (planar waveguides), we focus our attention on the theory of guided modes in two-dimensional structures such as channel waveguides, which are the basic elements in photonic integrated circuits.

Chapter 4 is devoted to the coupling theory of modes in optical waveguides. The understanding of mode coupling is of vital importance for most integrated optical devices. This chapter includes the study of optical power transfer between waveguide modes, whether it is energy transfer between co-directional or contradirectional propagating modes. Also, waveguide diffraction gratings are introduced in this chapter, as they are key integrated photonic elements which offer an efficient and controllable way of exchange power between waveguide modes.

Finally, Chapter 5 deals with the theory of light propagation in waveguide structures. The problem of optical propagation in waveguides is reducible to solve light paraxial propagation in inhomogeneous media, where paraxial means propagation mainly along a preferential direction. Although we will discuss several approaches to this problem, we will focus on the beam propagation algorithm, known as beam propagation method (BPM), which is a step-by-step method of simulating the passing of light through any waveguiding medium, allowing us to track the optical field at any point as it propagates along guiding structures.

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Further Reading

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