Nowadays, there are three main types of transmission media available: copper wire, free space and light. Cooper wire, into which the coaxial cable is included, is widely used and its principles and properties are well knwon: a signal is transmitted along the wire, either in analogic or digital form, to a receiver generally located at the end of the wire. Free-space is also commonly used. Clearest examples of this communication system could be radio and television. The use of light for communication purposes, has been used since the ancient times (see last chapter). Essentially, it consists on a light source, a transparent media in which light is confined (waveguide) and a photodetector.

Light guiding offers better properties as compared to coaxial and free space, as could be: **1. Bandwidth:** The capacity of carrying information depends on the frequency. The carrier wave in an optical waveguide is light, and it has a frequency several orders of magnitude higher than the highest radio wave. Thus, waveguides have a much larger bandwidth, which makes them suitable for high speed transfer data. Moreover, with multiplexing, hundreds of channels can be sent over a single fiber. Waveguides have potential frequency up to THz, although this range is far from being exploited today. The practical bandwidth of an optical fiber greatly exceeds that of cooper cable. Furthermore, the waveguide’s bandwidth has only begun to be used, whereas the potential of cooper cable is nearing its limits. **2. Low Loss.** This magnitude, together with the pulse broadening, determines the maximum distance at which information can be sent and recovered. As signals travel along the transmission path (cooper or waveguides) they lose strength. This loss is called attenuation or intrinsic losses. In a cooper cable, attenuation sharply increases with frequency: The higher the frequency of the carrier signal, the higher the losses. By comparison, attenuation in waveguides is insignificant even at frequencies up to 10GHz. Maximum frequency at which they can transmit information is not limited by attenuation, but indirectly by the dispersion phenomena **3. Electromagnetic immunity (EMI).** Due to the fact that materials used for the fabrication of waveguides are generally dielectrics, they remain unaffected under electromagnetic fields. This offers several advantages over cooper cables. Any cooper cable acts as an aerial, either transmitting or receiving. This causes the quantity of data transmitted or received to be progressively degraded, or even lost.

EMI control for cooper wires commonly involves adding shielded or coaxial cables, which undoubtedly causes raising costs, making waveguides more competitive. **4. Security.** It is virtually impossible to obtain information from a fiber optics without affecting the overall transmission. Since passivated waveguides do not radiate energy, proximity techniques for information reading also fail. Such security reduces data encryption costs. In harsh environments, as could be under strong electromagnetic fields and highly explosive or toxic environments, two principal features of waveguides greatly overcome those of the cooper cables: Firstly, light do not shortcut and a power excess in the waveguides generally do not cause device malfunction. Thus, the impossibility of making sparks is by itself a major advantage. Secondly, by the combination of two fields of waveguides, that is, fiber optics and integrated optics (or even only fiber optics), it is possible to obtain remote sensing. That is, knowing that the best available fiber optics (without Er-doping) has a transmission losses of about 0.2dB/Km, it is possible to place either the light source and the detector (which need an electric supply), far away from the atmosphere/material to be sensed. Connection between fiber optics and integrated optics devices is still today a bottleneck that prevents its mass implantation. However, progresses are continuously made and it is expected they soon reach the market. **5. Weight** When comparing a fiber optics and cooper cables with the same carrying information, it is observed that the latter is much weighty since it requires more lines than the fiber. As an example, the standard single-conductor fiber cable weights 1.2Kg/Km. A comparable coaxial cable would weight 10Kg/Km. In applications where weight is crucial, as could be aerospatial or shipping, weight saving allows for more cargo, higher altitude, greater range or more speed. **6. Small size** Waveguides are smaller than its cooper counterparts, and a single fiber optics can replace several cooper conductors. A cable containing 144 fiber optics in a 12mm diameter has the capacity to carry nearly two million calls at the same time. A comparable coaxial cable would be about nine times wider.

Formerly, telecommunications requirements caused major technological advances in fiber optics that caused miniature optical transmitters and receivers to be fabricated, which were the first devices obtained in integrated optics. However, its application fields fastly broadened to many others, as could be spectrum analyzers, gyroscopes, optical switchers, routers, converters and optical sensors.

There are two basic forms to obtain integrated optical circuits (IOC). The first one, the hybrid, requires the use of at least two different substrate materials which are somehow bonded together in a single device. The second is the monolithic IOC, in which a single substrate is used for all the required components. Obviously, whether a light source is required, materials with a direct bandgap are necessary, as could be GaAs, GaAlAs, GaAlP, GaInP, InP, GaN and other III-V and II-VI compounds. Passive materials as silicon, glass or $LiNbO_3$ are the most commonly used in hybrid integration, since its indirect bangap prevents from obtaining reliable light sources. However, a significant effort is being made in order to obtain light emitters and amplifiers by incorporating Er^+ ions into these substrate materials specially for telecommunication purposes (erbium ions emit at 1.533μm).

The major advantage of hybrid approach is that IOC can be obtained using the well-known technology of both fields. Its major disadvantage is the possibility of misalignment or even failure during the assembly process because of vibration or differences in its expansion coefficient. As an example, in fig. 1, the basic configuration of a micromechanized Michelson-Morley interferometer is presented. The laser source is based in III-V technology over a GaAs substrate. Simultaneously, in a silicon wafer, a micromechanization process has been done in order to obtain three Fresnel lenses, a beam splitter and a 45º tilt optical mirror. After ending both fabrication processes, the final structure has been assembled, bonding the laser to the silicon wafer.

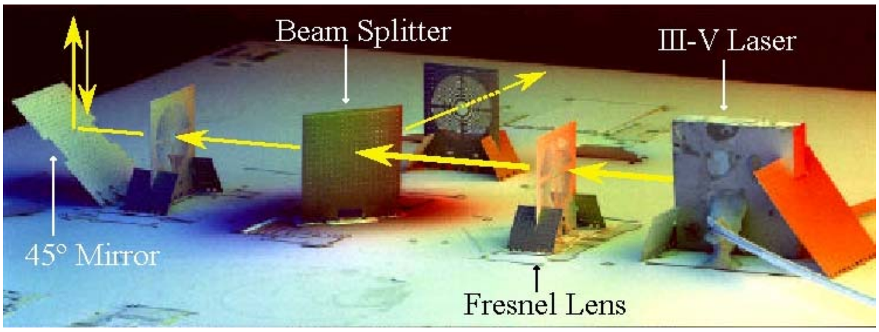

Fig. 1.1.: Micro Michelson interferometer using hybrid technology. After **[1]**

A second example consists on an optical router. Three fiber optics are arranged at the Si substrate as shown in fig. 2. Using micromechanization, a silicon mirror has been defined at the region between the fiber optics in such a way that light coming from the fiber at 0º is reflected at the mirror and is injected into the fiber at 90º. On the contrary, if the mirror is somehow removed, light from the fiber at 0º is collected by these located at 180º. There exist different mechanisms by which the mirror could be moved. As an example, a comb-drive system, shown in fig. 2b could be used. Basically it consists on two interdigitated structures in which a potential is applied. By ways of electrostatic forces, the displacement is achieved. Main drawbacks of this system are the high voltage needed and the non-lineal movement of the mirror with the applied voltage.

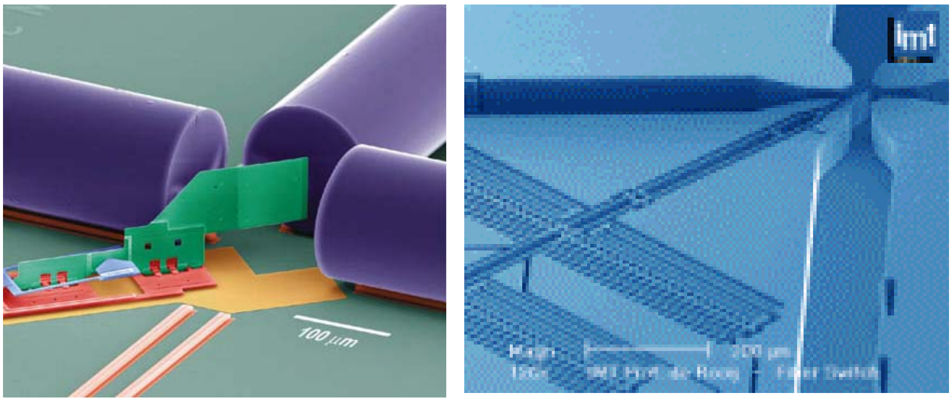

Fig. 1.2.: Optical router using hybrid technology. After **[2,3]**

A third example, still in development, is related to chemical sensors. As can be seen in fig. 3, the liquid to be measured is injected in a micromechanized glass pipe and passes through a cuvette where optochemical sensors are located. Light injected by either a fiber optic or a waveguide suffers from variations in its spectral properties while passing thought the liquid. When the beam reaches the spectrometer, it is decomposed in its wavelengths as if it was a prism. An array of photodiodes, made on a different substrate, give a measure of the power at each wavelength. Thus, knowing the absorbance spectra variation as a function of the amount of substance to be detected, measurements without direct contact can be done.

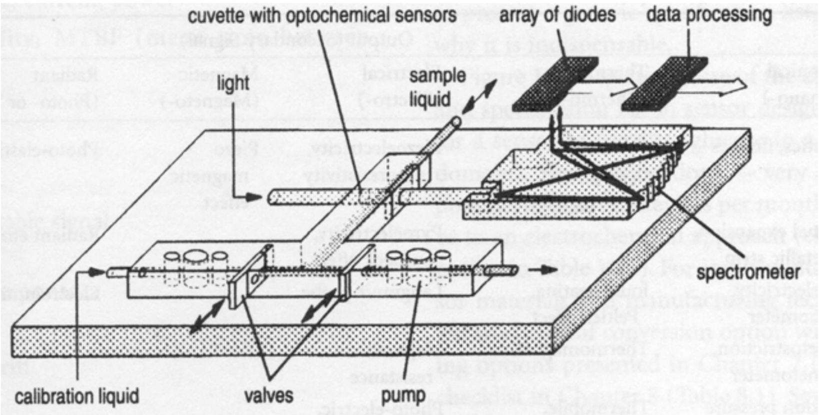

Fig. 1.3.: Optochemical sensor using hybrid technology. After **[4]**

Although the hybrid integration has provided with complex devices with accurate response, these kind of devices normally require a manual alignment of the different part, which, in turn, causes a dramatic increase of their costs. On the contrary, the monolithic approach is much cheaper in mass production, because automatic batch processing can be used. Thus, monolithically IOC are likely to become the most common type in the near future. However, due to important backdraws in monolithic integration, the first commercially available integrated optics products are based in hybrid technology (acusto-optic and electro-optic modulators in lithiun niobate and photodiode arrays in silicon).

As it was previously mentioned, not all materials are suitable for integrated optics devices. Although a material could be appropriate for a given application in integrated optics, it may have a poor response for another. However, there exists some general requirements for all materials, that is they have to be transparent at the working wavelength, linear, isotropic and homogeneous. Other material properties allow a device classification.

1. Passive/Passive dynamical devices. Materials whose properties remain unchanged while the device is working. Thus, light could only be affected either by the geometry of the device or by external perturbations. Examples of this category are arrayed waveguide gratings (AWG, for (de-) multiplexing purposes), Interferometers (Mach-Zehnder, Michelson, Sagnac), polarizators, directional couplers, 3dB splitters, multimode interference couplers (MMI) and gratings. There are no additional requirements for the layers as those above mentioned.

2. Devices based on specific material properties. Under this category a large number of transduction principles could be included. However, We will restrict ourselves to the most used in IOC, that are electro-optical, thermo-optical and acusto-optical properties. Light sources (Laser and LED), although could also be included in the electro-optical mechanism, will be treated as active devices, as they are usually found in the literature.

The material with best electro-optical properties up to date is the lithium niobate. Although its anisotropy causes to be polarization dependent, its high transparency in a broad range (0.12-12μm) together with the relative easiness in the IOC fabrication process (by ion diffusion) makes them optimum for optical routing and switching. Major disadvantages are its high cost and anisotropy. Several polymers have recently shown good electro-optical properties, but they often shown short term stability.

Although silicon has a low electro-optic coefficient, it has relatively good thermo-optic properties. The deep knowledge of its properties and the available technology makes it the most suitable for this application. The major drawbacks are its slow response (ms) and the high input power needed for refractive index modification.

The most known example of acusto-optical effect is the surface acoustic waves (SAW), in which gallium nitride and lithium niobate are commonly used. The major advantage of this type of effect is that the reflected angle does not depend on the variation of the refractive index caused by the perturbation. However, it requires relatively long devices in order to obtain efficient reflection.

3. Direct bandgap devices. Monolithic integration can only be obtained by ways of direct bandgap III-V and II-VI semiconductors. Between these materials, the ternary and quaternary compounds are preferred since the bandgap of the material can be tailored to the desired wavelength simply by changing the relative concentration of the elements. Light emitted by semiconductors is given by the bandgap energy, but they also absorb all frequencies higher or equal to the emitted. Thus, if a light source, the waveguide and the detector are all obtained in the same substrate, intrinsic losses at the waveguide would be very high, while photodetector response would be clearly

unsatisfactory. One interesting solution is changing the composition in each part of the IOC in order to eliminate this drawbacks.

The GaAlAs/GaAs is one of the precursors of monolithic integration working at a wavelength of 0.8µm. The components obtained with these semiconductors are generally used for short-range interconnects. Due to its high refractive index and the high index contrasts, layers are generally very thin and with a high numerical aperture, causing its insertion losses to be very high. Changing the relative concentration of the ternary system, it is possible to obtain light at wavelengths between 0.65 an 1.7µm. Moreover, they show relatively large electro-optic and acusto-optic effect (but minor than LiNbO$_3$), making them useful for switches and modulators. The increasing use of these compounds has significantly reduced its price. Another point that has to be taken into account is the fact that GaAs and AlAs almost have the same lattice constant (5.646 and 5.369Å, respectively). Thus, consecutive layers with different concentrations of Al in the GaAlAs compound does not cause lattice strain in the structure. This is particularly important in the fabrication of multilayered, heterojunction lasers. In order to obtain monolithic laser sources at the telecommunications range (1.3/1.5µm), the GaInAsP/InP system was developed. Although their lattice constant do not match as good as with the GaAs/AlAs compounds, it is possible to obtain highly efficient laser diodes at wavelengths where losses in fiber optics are extremely low. However, they also have a high refractive index, which requires reduced dimensions for monomode behavior and increases its insertion losses.

For a long time, it seemed that III-V and II-VI technologies would have major application than silicon (and also polymers and LiNbO$_3$). However, the fabrication complexity, yield and cost of the III-V and II-V technologies, their insertion and attenuation losses as well as its significant polarization dependence keeps the situation still today balanced.

Objectives of the thesis

This thesis tries to summarize all the work done in the last five years at the Centro Nacional de Microelectrònica (IMB-CNM-CSIC). And pretends to be a continuation of the previous research done by Dr. Carlos Domínguez, Dr. Ignacio Garcés, Dr. Mauricio Moreno and Dr. David Jiménez. On the basis of their work, the main idea in which this thesis should be focused was the development of new numerical techniques, stabilization of the integrated optics technology, development of new integrated optical devices and their characterization.

With these milestones in mind, the research started either with the analytical and numerical analysis of slab ARROW-A structures. For this latter purpose, the Non-Uniform Finite Method, together with the Effective Index Method and the Beam Propagation method was implemented, and their results were compared with the bibliography. However, for some concrete applications were NU-FDM was not reliable enough, the commercially available Finite Element Method, ANSYS, was used.

Once the numerical tools were available, major efforts were focused on a deep analysis of all the parameters involved in ARROW structures, whose results are shown in chapter 2, and its effect on the overall properties of the waveguide were studied. Once their properties were known, its optimization process was straightforward. At that point, first ideas concerning new optical devices or the possibility of applying ARROW structures to well-known devices began to appear. Basic ideas concerning its expected behavior are also presented in chapter 2.

Main problems arose during the fabrication processes, shown in chapter 3. Actually, looking in perspective, it could be considered even as logical, since it was by far the most critical point. Although a pre-existing integrated optics technology was already established, in some situations the layers forming the ARROW structure cracked due to excessive mechanical stresses. Since it apparently was a random behavior, a deep study of its mechanical properties was compulsory. Working conditions were varied, obtaining for each layer its FTIR spectra, its refractive index, its thickness, and its radius of curvature, These measurements allowed correlating the stress with the impurity concentration and the refractive index. Thus, the optimum deposition conditions that permit obtaining the optimal waveguides studied in chapter 2 were defined. At that point, it became clear that further study of the rest of the clean room process would be necessary if the new devices were to be done. Thus, the effects of Al deposition and deep etching with Al mask of the different layers (SiO_2, Si_3N_4 and Si) were analyzed. Again, it was observed that yet optimized, mechanical stresses in the ARROW structure were high and accurate deposition and etching conditions were required. Finally, the effect of having a rough surface would cause insertion losses to be extremely high. This fact forced polishing the facets of the waveguide until the defects were much smaller than the expecting working wavelength, which was fixed at 633nm.

Once the numerical and fabrication tools were ready, integrated optical devices began to be accurately analyzed, either by simulations and by considering their technological difficulties. Among all the proposed devices, these shown in chapter 4 were the selected for fabrication. Reasons why choosing these devices range from simplicity and originality to application and challenge. Although they were (and in some cases still are) some drawbacks and delays, it was possible to obtain most of them.

Finally, the experimental results, shown in chapter 5, allowed confirming the simulation in some occasions, while the mismatches between both results forced us to find factors that had not been taken into account at the simulations. As an example, the periodical exchange of power between the measured data and the predicted results in the directional coupler were so diverging that it had to be something that explained that result, and it was found that the main responsible of the change in the period was the wall tilt. It can also be observed in chapter 5 that devices are progressively getting more complex, thence, more difficult and challenging: Starting from the required accuracy in the Mach-Zehnder Interferometer, the 1st generation of absorbance sensors was completely modified, optimizing the input waveguide so as to permit a 180º bending. Moreover, a self-aligned structure was designed from which the alignment would unnecessary. Finally, the optical accelerometer was perhaps the most difficult, however exciting project in which we were involved in. Although it was impossible to obtain the diaphragm configuration, results obtained with the misalignment sensor were better as those observed in literature. Moreover, what was even more interesting was the fact that it was possible to match two apparently contradictory technologies: ARROW

waveguides, with thick multilayer structures, and micromechanization, that requires as less materials as possible and nothing but silicon on the bridges to avoid bimetal effect.

Bibliography

[1] www.ee.ucla.edu

[2] www.bell-labs.com/news/1999/ february/23/1.html

[3] www-samlab.unine.ch/Activities/ Research/research.htm

[4] M.Madou. *Fundamentals of Microfabrication*. CRC Press. 1997