Integrated Optics: The history and the future

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Abstract: *The continuous improvement of microtechnologies and the recent and very fast development of nanotechnologies have drastically modified technical and economical landscapes in many fields of activities. It's particularly true in optics because of the special position of the visible and near infrared optical wavelengths at the border of the micrometric and the nanometric world.*
Integrated optics which is now almost 30 years old is one of the more relevant fields to illustrate this double impact. This presentation will try to summarise the long and attractive way followed since the end of the 60's by one of the more fruitful branch of optics and to foresee some of its future developments.

Introduction

It is now 28 years since the Bell System Journal published a special issue on integrated optics and opened the way to one of the largest field of scientific investigation in optics. Many very attractive things have been done both in integrated light sources, detectors, optical components and systems and have led to a lot of technical breakthroughs.
One of the encountered difficulties which explains the wealth of integrated optics as well, was the strong diversities of materials and technologies studied and used in this field always balancing between the dream of monolithic integration and the more pragmatic approach offered by heterogeneous assemblies.
It's however clear that the huge diversity of functions and the high level of performances required to achieve an all integrated optical circuits especially in the field of optical communications increase drastically the difficulties to find an ideal substrate.
From the end of 90's, many laboratories, on the track of NTT and LETI, investigated hybrid solutions based on silicon. This hybrid approach associating sometimes both integrated optics and micro-optics became more and more developed around the world.
Curiously, the internet revolution which have been allowed by optical fibres and for a large part by integrated optics components, instead of marking the 'triumph' of integrated optics, has led to one of the worst technical crisis and to a drastic change in research orientations: silicon could once again be the winner of the battle.
I am now going to tell you this history which can be seen like a saga and to give you some indications to foresee the next episode.

Infancy and childhood

I believe that the real beginning of integrated optics is associated with the Bell System Journal issue of September 1969 where one can find some of the basic publications of E.A.J.Marcatili, D.Marcuse, P.K Tien, R.Ulrich, H.Kogelnik or I.P.Kaminow who can be considered, together with A.Yariv, as the fathers of this field.
At this time, all the dreams were allowed and nobody had an objective idea about both attainable performances and practical limitations [1].
At the end of the 60's, the best optical fibres exhibit typical propagation losses of about 20dB/km and laser diodes working at room temperature did not yet exist.
One of the main events was the patent of the Russian team led by Z. Alferov at Ioffe Institute concerning the semiconductor laser heterostructures. It was really the start of the laser diodes development with all the applications you know today.
At this time and during several years, the best wavelengths for optical fibres was not yet in the range 1.3-1.7µm but around 0.8µm. Fortunately, the easier heterostructures which can be achieved with a III-V direct gap semiconductor were founded in the ternary family GaAs/GaAlAs emitting in this spectral range. However during several years many laboratories worked hard to improve the reliability of the diodes, to increase their lifetime and to understand some of physical phenomena well controlled today. Of course all these works have been a good appetizer for mastering more complex heterostructures like quarternary heterostructures on InP [2].
In 1973, I was 25 years old and I begun a Ph.D. thesis at LETI on ion implanted waveguides on zinc telluride, a II-VI semiconductor which exhibited high

electro-optics coefficients and could be a candidate for efficient modulators [3].

Early in the 70's, many laboratories began to achieve optical waveguides on lithium niobate by different approaches including the now well known titanium in-diffusion or proton exchange techniques and to propose different schemes of modulators based on coupled mode theory. I remember the name 'COBRA', then 'BOA' and a little bit later 'timed COBRA' with alternate electrodes configuration which became the reference structure for modern modulators[4]. At the same time appeared the first publications showing the strong advantage of integrated optics and optical confinement to achieve non-linear optics devices [5].

For my part, it appeared clearly that ZnTe was not a good choice and after many efforts and fights with II-VI compounds technology very far from the maturity, I became to think that silicon could be a better way. This idea was not really surprising if one remembers that LETI is at first a microelectronics laboratory.

Between 1980 and 1987, two basic technologies were experimented in my laboratory: IOS1 and IOS2 using respectively silicon nitride and doped silica waveguides. Several basic devices were realised by CVD techniques with a good level of performances [6]. It was the first step of the silicon based technology developments extensively studied around the world some years later. At the same time, the laboratory of M.Kawachi at NTT published the first flame hydrolysis silica waveguides [7]. In both cases, it's the first time that propagation losses could be given in dB/m and not in dB/cm offering a lot of possibilities for new devices in the field of communications and in the field of sensors as well [8].

Few years earlier, ion exchange on glass developed by glass manufacturers in Japan were applied to integrated optics by Pr Chartier and led to a large interest around the world because of the greater simplicity and the lower cost of the fabrication process [9].

Some attractive developments have been done on polymer waveguides for passive and active devices as well [10].

On the other hand, many progresses were done in integrated lasers: towards longer wavelengths to take advantage of the new performances of optical fibres and their propagation losses less than 0.2dB/km, towards smaller wavelengths to join the need of new application fields as optical storage. That meant new III-V semiconductor materials, new type of heterostructures involving quantum wells, strained layers and new concepts of light sources illustrated by VCSEL[11].

Adulthood and maturity

At the end of 80's and at the beginning of the 90', integrated optics becomes a mature technology and optical communications were more and more the motor of its development. All big industrial groups made strong efforts both in silicon based, lithium niobate, III-V or even glass technologies.

A lot of attractive components and devices have been proposed showing the wealth and the maturity of integrated optics [12].

On the other hand, the possibilities to fabricate very long waveguides with low attenuation give new possibilities in the field of sensors and many demonstrations have been done during this period.

One of the best demonstrations of this teaming of ideas is probably the so called 'phasar' invented by Meint Smit which perfectly illustrated both the maturity of the field and showed that there was always the place for innovation [13].

Another smart demonstration of the potential of integrated optoelectronics has been given by the optical fibre gyro. This device combined a lot of progresses including low loss maintaining polarization fibres, super radiant light sources, lithium niobate phase modulators to optimize both sensitivity and low drift in a Sagnac loop [14]. At this time, I was in charge of different training sessions on optoelectronics in University and high school and fibre gyro was my favourite example to illustrate the diversity and the potential of optoelectronics and the scientific process of thinking.

Combination of integrated optics and MEMS technologies brought also new attractive devices, for instance in the fields of sensors [15].

However, in spite of these huge developments in laboratories and in industrial companies, the connection between all these heterogeneous components remains the stumbling block of integrated optics.

Several attempts tried to overcome this difficulty or to give technical solutions able to integrate this step in the component fabrication process. In silicon based technologies, U-groove techniques have been proposed for efficient optical coupling between fibres and silica waveguides [16].

Hybridization approaches derived from flip-chip techniques has been developed to align the different components required to build a complete optoelectronic module [17]. All these attempts have demonstrated interesting possibilities; however they generally led to additional steps in the process which of course penalized the economic balance.

In parallel, segmented waveguides have been demonstrated as one of the more attractive approaches to adapt locally different mode structures and reduce the connection losses [18].

Glory and fall

The beginning of the internet revolution at the end of the 90's can be considered as the hour of glory for optical communication and for integrated optics technologies.

It is interesting to note that among the large panel of studied technologies, all of them have led to industrial developments and to commercialized devices. Silica based technologies mainly for phase array mux-demux, ion exchange on glass for power splitters, lithium niobate for modulators and of course semiconductors for light generation and detection [19].

So there were no losers, but as we know no real winner as well.

All big industrial groups have invested a lot of money to respond to the large demand for long haul communications. Many start-ups have been created to anticipate the appetite of high rate transmissions needed in metro and access areas which were the expected following markets.

All actors which have lived this period have a lot of incredible anecdotes to tell, and it could be interesting to understand what happened during these few years and why many people among the more pragmatic one, scientists, industrials, economists lost the sense of reality.

The crisis had of course several explanations.

I guess that the first one is the extraordinary jump brought by optical communications and optical fibres. It was maybe the first time that a given technology gave the possibility to increase the existing state of art by several decades, leading of course to a strong shift between the social needs and the technical capacity. In microelectronics, the evolution was graduated and the power of the processor grew step by step with the decrease of the transistor size: so the technology has followed the market demand. In optical communications the technical jump was too high and arrived too suddenly.

I think also that there was a common blindness between scientists, which dreamed of optical communication for more than 30 years, and economists who have overestimated the social acceptance and have made subjective analyses.

Finally, the shift lasted maybe less than ten years but for an economical point of view it was extremely long.

The revival

At the end of the crisis, as in the fable, all don't die but all were damaged.

The good side of the medal is maybe the complete calling into questions of the integrated optics field with in many cases the birth of new concepts.

Even if traditional technologies can always be improved, the silicon nanophotonics seems the new way to follow but with very different approaches compared to those developed at the beginning of 80's.

High index contrasts are now the basic structures and SOI substrates seem to be the new materials of optoelectronics. New companies are now in the race, mainly in the field of microelectronics where integrated optics may bring a smart solution to break the deadlock of interconnects [20].

It is curious to see the shift of performance requirements compared with those of previous fields. Losses can be expressed in dB/mm and no longer in dB/m, but the level of integration will be probably ten or hundred time higher.

That suppose of course a very high control of the technological level but advanced microelectronics seems able to bring that. In the same time, the problems of connection are changing ever drastically by the systematic use of hybridization technique or by the integration of all components including light sources in the silicon itself. The complete compatibility with CMOS approach is the new Grail to reach; it can lean on very efficient tools and on some high volume market applications.

Intel and all microelectronics actors are the new leaders of this new optoelectronics field but, by the way, is that optoelectronics yet? [21]

In Rhône-Alpes region we have the chance to work with two of the main actors of this revolution as ST Microelectronics and SOITEC, the world leader of SOI substrate.

So good luck to integrated nanophotonics; I would only like to wish to the new actors to have as many dreams as we have had.

PS: Many information and analyses on this evolution can be available on the website MONA: www.ist-mona.org.

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