Multi-functional optical devices and subsystems integrated on a chip

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Abstract

This review article summarizes the opto-electronic integrated devices and subsystems research line activities, developed at the Optical and Quantum Communications Group (OQCG). The research line approach starts at the conception and theoretical development of new photonic devices on a chip, followed by computer aided design, chip fabrication (outsourced) and device testing at the component and systems level in the OQCG laboratory facilities.

Keywords: integrated optics, modeling, simulation, arrayed waveguide grating, cross waveguide grating, semiconductor optical amplifier, ring resonator, indium phosphide, silicon photonics, optical time domain multiplexing, microwave photonics, multi-wavelength laser, optical label swapping

1. Introduction

The efficient exchange of information in actual society is recognized as one of the most important catalysts for development. In the early stages of life on earth, evolution started by communication between simple cells and bodies using chemical reactions. Evolution of humans further away than other species is based on their capability to adapt and to communicate. Nowadays, societal development is strongly connected to a fast and efficient way of exchanging information. The development and social adoption of the Internet as the principal mean for long distance fast communications, is supported by ground infrastructures that mainly rely on the exchange of light signals using optical fibers. The invention of the laser on the 60's, enabled the science of mastering light signals, processing and using them for ultra-long distance communications. Technology developments in the field are driven by daily increasing demands on the amount of information to be exchanged. Therefore, telecommunication providers face the trouble of squeezing their available infrastructure to the maximum. Moreover, more and more physical space is needed to settle information transmitters, receivers and rely data stations, with increasing electric power consumption. To cope this problem, the field of integrated optics aims at grooming several functionalities for such data stations in the smallest space and with the minimum power consumption.

Integrated optics circuits are in shape devices similar to the widespread consumer electronics devices, as the printed circuit boards one can find inside a home computer. The very significant difference is that the latter use electric signals, whilst the former use optical signals to work with. This difference makes the subject of integrated optics a complex science involving from chemical and matter sciences and processes, to build the support boards for the circuits, to design engineering and signal processing to master the light therein. In integrated optics, the term wafer is used instead of board.

This review article is a summary of the activities carried out to produce, from the perspective of an electronic engineer, multi-functional devices on an optical chip, in order to generate and manipulate light signals for telecommunications.

2. Research line approach

From an electronic engineer perspective, the needs and constrains are driven by the targeted application of the device. The first question is if the device will have either to generate internally light signals, or to process light signals injected into it by whatever the means. The answer to this question is related to choosing a given technology, the supporting technology, that is, the materials used to build the wafer for the circuits. Materials that can generate light are known as active materials, whilst the others are known as passive. Therefore one refers accordingly to active or passive devices.

Though there are several technologies being used for integrated optics [1], two of them are of superior interest: first, Silicon-On-Insulator (SOI) technology which is passive, relevant due to its compatibility with consumer board electronics, i.e. the ability to integrate optics and consumer electronics on the same chip; second, Indium Phosphide technology which is active, due to its capability of (re)generating light. A good review of both can be found in [2] and [3] respectively, and the references therein.

Integrated optics devices are the optics counter part of microelectronics.

2.1 Design approach

In whatever the technology, the designer is provided with the description of the different layers the wafer is composed of, being the different material films grown to form the wafer. This is known as the layer-stack. The very first step is then to engineer the channels, the term waveguides is used, for the light to go through the chip, technically called the propagation of light. The waveguides have typically a rectangular cross-section. According to the layer-stack and material physical properties concerning the light, typically the refractive index of the material in each layer, the cross-section (width and height) is defined to obtain the desired propagation conditions. This is an electromagnetic problem consisting on finding the shape and propagation speed of the light in the medium, both known as the supported modes of the waveguide. At this step computer aided design comes into place.

The tools solving this problems are known as mode-solvers. These tools can be found as commercial or freely available software packages. A good example of the latter is the Waveguide Mode Matching, Wmm, tool from [4], which is available under General Public License (GPL). Making use of these tools one can analyze the propagation conditions of light for a given technology and waveguide cross-section. In Fig. 1, an example is shown for a waveguide on SOI. The lower layer, or substrate, is SiO_2 with refractive index 1.45, and the waveguide layer, or core, is Si with refractive index of 3.5. The core has a cross-section of 500 nm x 220 nm. These are the propagation conditions of straight waveguide sections. However, practical devices need also curved, or bent, waveguides. In a similar way, mode-solvers must be used to engineer the bent waveguides. Typically a minimum bent radius is found in such a way the light remains inside the waveguide. Below this radius, the light is radiated out, and therefore lost. This is analogous to a car travelling at a given constant speed along a road: as long as the road turns are smooth enough for the speed, the car will remain in its way.

Once the light propagation conditions are known, the next design step involves the targeted device. There are several functional blocks one may use in integrated optics. Without being extensive, they are summarized in Table I. The interested reader may refer to [1] for further details on the devices. In the design process, numerical tools to analyze the propagation of light can be used. Depending on the nature of the device being analyzed, several methods exist. Briefly, if there is one dominant propagation direction, the Beam Propagation Method (BPM) [5] is the most widely used tool. When omni-directional propagation is needed, i.e. light is not bound to a preferred direction, the Finite Differences in the Time Domain (FDTD) method [6] and tools [7] are used. These late tools can be efficiently implemented using parallel computing, which is employed at the OQCG computer cluster [8].

After simulation and design, the waveguide structures and dimensions are defined. The last step prior to fabrication is the production of the mask layout file. There are several de facto standards, as the widely used Graphic Design System (GDS) file format, and also the Caltech Intermediate Format (CIF) file format. Several GPL libraries are available for the designers to produce layouts in these formats [9] [10]. There also GPL mask file viewers/editors as for instance [11] [12]. An example of a layout file is shown in Fig. 2.

2.2 Device fabrication: the foundries

The facilities of the OQCG do not include a foundry, i.e. a facility where chips are fabricated. Howe-

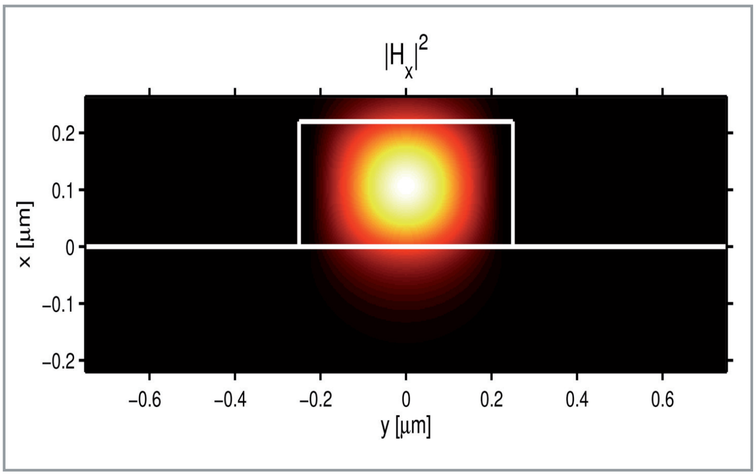

Figure 1. *Fundamental mode of a SOI waveguide of cross-section (width x height) 500 nm x 220 nm. The propagation constant is $\beta=9.77$ rad/μm, or equivalently the effective index is $n_{eff}=2.41$.*

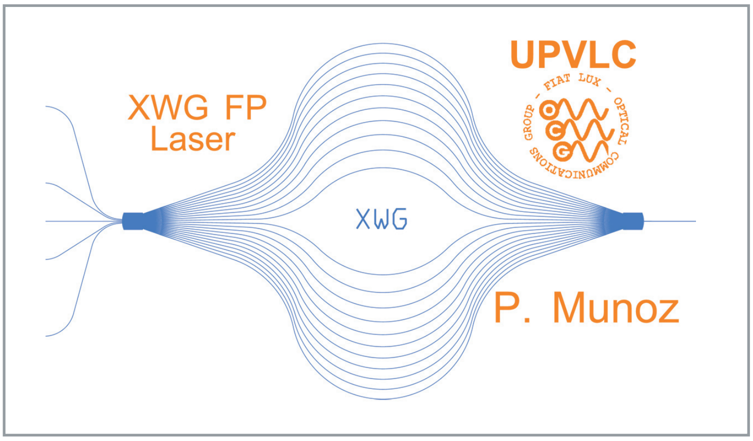

Figure 2. *Layout of a Cross Waveguide Grating (XWG) device.*

Device	Abbreviation	Functionality	Nature	Control
Waveguide	WVG	Transport light	Passive	-
Y-branch	Y-br	Split light in two branches	Passive	-
MxN coupler	COUP	Split/combine light in/from N/M branches	Passive	-
Phase modulator	PM	Waveguide with electric contact to control the phase shift of light	Passive	Electric
Amplitude modulator (electro/optic modulator)	EOM	Device to convey an electric signal into optical signal	Passive	Electric
Semiconductor Optical Amplifier	SOA	Waveguide with electric contact to amplify light signals	Active	Electric
Distributed Bragg Reflector	DBR	Device to reject a band of frequencies from an optical signal	Passive	-
Laser	Laser	Device to provide a narrow spectral line of light	Active	Electric
(Ring) Resonator	RR	Device used for recirculation of light	Passive	-
Arrayed Waveguide Grating	AWG	Device to split/combine the different frequencies of light signals	Passive	-

■ **Figure 3.** *Summary of integrated optics building blocks. Refer to [1] for details.*

ver, cooperation at a European scale, enabled by the European Commission funded network of excellence ePIXnet (European Network of Excellence on Photonic Integrated Components and Circuits -www.epixnet.org-) [13], has put into place several foundry, or platforms, to provide fabrication services for fab-less laboratories. Concerning the main technologies, mentioned previously, there exist two platforms available to provide fabrication services.

The Silicon Photonics platform, known as ePIXfab [14], provides fabrication on SOI passive technology using a CMOS technology fabrication line. The JePPIX platform [15], provides services for fabrication of InP active/passive devices. The approach of these foundries is to perform shared runs, in which users share wafer space, therefore being a cost-effective and affordable service.

The foundries operate by issuing calls for design, and typically perform fabrication runs every four months. Designers are equipped with guidelines and software tools to generate a computer digital file containing the designs. This is known as the mask layout. For these two platforms, the file is used to fabricate a hard (metal) mask, that is used later on to transfer the patterns therein to the wafers.

Afterwards, devices are cut into pieces, the terms diced or cleaved are used and sent back to the users. In some cases the sides of the chips, the facets, have to coated with high-reflection or anti-reflection materials, depending on the on chip devices functionality. Other platforms operate from chip outwards, for instance ePIXpack -www.epixpack.eu- which handles the packaging of chips, involving attaching optical fibers, electric contacts, chip enclosure and thermal control amongst other features. The packaging is performed for very successful chips, and in the case the device must the used in systems environment.

Some photographs of realized devices are shown in Fig. 3.

2.3 Device characterization

The OQCG laboratory facilities include an optoelectronic chip setup for bare chip (un-packaged, with no fibers, with no electric contacts) characterization. A diagram of the chip, along with some photographs, are shown in Fig. 4. The scheme in Fig. 4-(a) shows the setup is composed of different parts for light in/out coupling to/from the chips. Fibers and/or microscope objectives can be used. The chips are mounted onto a vacuum chuck. All the structures are supported on top of micro-positioners that provide alignment at the nanometer level.

Measurements that can be performed at a component level in the setup include transmission and emission measurements. The former involves using light from an external source, either laser or broadband optical sources. The light is coupled into the chip from one facet, and out coupled from the opposite one. Emission measurements involve chips that can generate light, by for instance biasing an active area of the chip. Therefore, coupling light in is not necessary. In both measurements, the out-coupled light is analyzed by means of optics instrumentation: power meters, optical spectrum analyzers, lightwave component analyzers, bit error testers, to name a few.

In Fig. 5-(a), the photograph of light spot out-coupled from an optical waveguide is shown. This photograph is taken using a phosphore camera. The chip was illuminated from the opposite (input) facet by a beam colimated using a microscope objective. The light fringe above the spot is due to diffraction at the input facet. In Fig. 5-(b), the simulation and measured spectral response of a Cross Waveguide Grating (XWG) device are shown.

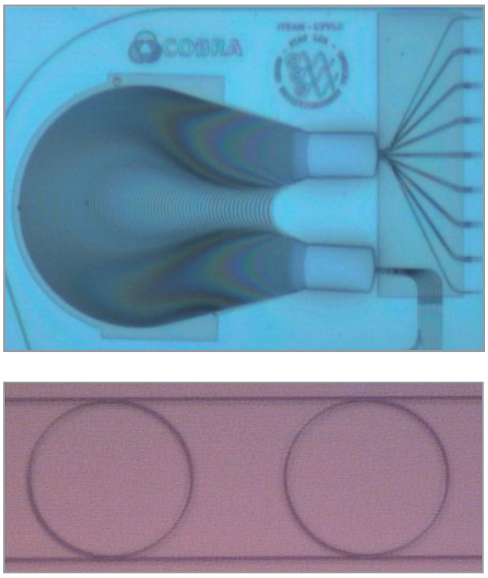

Figure 4. *(a) InP AWG (JePPIX)*
(b) SiNx Ring Resonators (ISOM-UPM)

3. Projects and devices

3.1 ePIXnet JRA InP AWG

The European Network of Excellence on Photonic Integrated Components and Circuits (ePIXnet) [13] is a Network of Excellence (NoE), funded by the European Commission through the Framework Program 7, FP-7. The NoE is structured into Joint Research Activities (JRAs), and technology platforms, as the mentioned above. The OQCG is the coordinator of the JRA "Active phased-arrayed based devices", abbreviated as "InP AWG". This activity has been carried out for more than two years, starting at September 2006, and ending in February 2009. The activity partners besides the OQCG are: Politecnico di Torino (Italy), Cobra Research Institute (The Netherlands) and Alcatel III-V (France). The aim of the activity has been to develop active integrated optics multi-wavelength devices, (a) transmitter/receiver for optical burst/packet switched networks, (b) multi/demultiplexers for optical time domain multiplexed networks, (c) linear and ring lasers (d) wavelength-tunable devices. The technology employed is InP, enabled by the JePPIX platform [15].

Several successful devices were realized in the life of the project. First, a tunable optical pulse shaper. The device consists on two AWGs connected by a set of PMs. The spectrum of the input optical pulse is sliced by the first AWG. The phase of each slice can be adjusted individually. The second AWG recombines the slices. The proper set of the PMs may lead to pulse compression in time, therefore enabling high-speed optical time domain multiplexed (OTDM) communications, as more pulse can be put together when their duration is small. The interested reader is referred to [16].

Several foundry services can be used for fab-less laboratories.

Second, a novel device concept was developed from theory to practical realization, the Cross Waveguide Grating. The device resembles an AWG, however the spectral properties are different. The overall functioning is similar to the combination of a power coupler and two AWGs, in a single device. Details can be found in [17] and in [18]. The XWG combined with SOAs can be used as multi-wavelength laser and terahertz sources.

The third device is a multi-wavelength Sagnac cavity interferometer, based on AWGs. Several designs exist, and fabrication is pending at the time of writing. The concept and theory can be found in [19]. The device can be used as a time demultiplexer for multi-wavelength OTDM networks. The advantages of these designs over the regular Sagnac interferometer is that each wavelength (data channel) can be processed independently, and that the optical control signals can be injected onto the device without the need of an optical coupler on Sagnac cavity, therefore minimizing the losses the data channel experiments [20].

Finally, and integrated optics label swapper for spectral coded labels [21] has been analyzed and designed for fabrication in InP too [22]. The device will use AWGs and SOAs. The application of the device is optical packet networks, where some wavelengths carry the data of the packets, and other the signaling, routing or label information. The device perform the exchange of label information between incoming and outgoing labels. The experimental demonstration of the three last devices is pending and expected to happen in the first half of 2009.

3.2 APRIL

The project "Active Passive Rings Integrated and Layered" is a small scale project funded by the Generalitat Valenciana government. The project is coordinated by the OQCG and devoted to analysis, synthesis and applications of integrated optics filters based on micro-ring resonator devices. The project runs from January 2007 to December 2008. Theoretical development of models and numerical tools for flat top devices was done [23], as well as the realization of some devices on silicon-nitride technology at the ISOM [24]. Techniques to translate flat top techniques to practical devices are being explored through some designs issued to ePIXfab [14]. These techniques are unpublished and under a patent application process. The devices will be available in February 2009, and characterization results are expected at the first quarter of 2009.

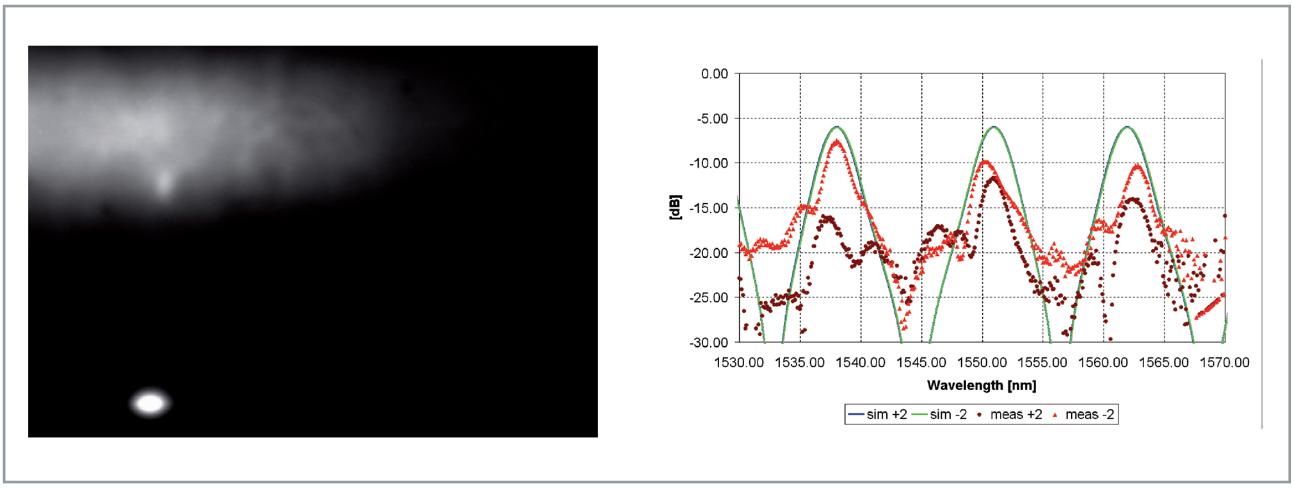

Figure 5. *Characterization, (a) photograph of the light spot and diffraction fringe seen at one of the chips facet, when light is injected on the opposite facet (b) simulation and measurements of the spectral characteristics of a Cross Waveguide Grating (XWG) [18].*

Chips are being developed for digital and microwave photonics applications.

3.3 CROWN

The project "Coupled Resonator Optical Waveguide eNgineering" is a national scale project funded by the Spanish Ministry of Science and Innovation, starting at January 2009 for a period of three years. The CROWN project addresses the development of design methodology and characterization of Coupled Resonator Optical Waveguides (CROWs) based devices on CMOS compatible Silicon-On-Insulator (SOI) technology for advance optical processing compatible with 40 Gb/s transmission systems and for a selected set of microwave/millimetre-wave photonics applications. Both topics are currently in the forefront research line of photonics.

The application of the devices to the optical processing of microwave/millimetre signals, such as filtering and delaying, and to provide error-free 40 Gb/s optical buffering of at least 10 bits will be proved. This figure is far beyond the requirements of frame alignment for on-board optical interconnects applications, as optical clock distribution, and a significant landmark for integrated optics buffering aimed at optical packet switched networks, using passive technologies.
The advantages brought by CROW devices for slowing down the propagation velocity of light will be explored and demonstrated experimentally for a selected set of microwave/millimetre-wave photonics applications including microwave signal filtering, optical beam-steering of antenna arrays, arbitrary generation of microwave signals, generation of flexible and arbitrary broadband phase shifts and true time delay lines for microwave and millimetre wave signals.

4. Conclusions

This paper reviews the activity carried out during the period 2007-2008 in Optical and Quantum Communications Group (OQCG), Insitute of Telecommunications and Multimedia Applications (iTEAM) within the research line of optoelectronic integration. Projects and devices for application on optical networks and microwave photonics have been realized and are planned for the near future.

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Biographies

José Capmany was born in Madrid, Spain, on December 15, 1962. He received the Ingeniero de Telecomunicacion and the Ph.D. degrees from the Universidad Politécnica de Madrid, Madrid, Spain, in 1987 and 1991, respectively. From 1988 to 1991, he worked as a Research Assistant at the Departamento de Tecnologia Fotonica, Universidad Politécnica de Madrid. In 1991, he moved to the Departamento de Comunicaciones, Universidad Politecnica de Valencia, Valencia, Spain, where he started the activities on optical communications and photonics, founding the Optical Communications Group. He has been an Associate Professor from 1992 to 1996, and Full Professor in optical communications, systems, and networks since 1996. In parallel, he has been Telecommunications Engineering Faculty Vice-Dean from 1991 to 1996, and Deputy Head of the Communications Department since 1996.

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Prof. Capmany has been a member of the Technical Programme Committees of the European Conference on Optical Communications (ECOC), the Optical Fiber Conference (OFC), the Integrated Optics and Optical Communications Conference (IOOC), CLEO Europe, and the Optoelectronics and Communications Conference (OECC). He has also carried out activities related to professional bodies and is the Founder and current Chairman of the LEOS Spanish Chapter, and a Fellow of the Optical Society of America (OSA) and the Institution of Electrical Engineers (IEE). He has acted as a reviewer for over 25 SCI journals in the field of photonics and telecommunications. He is the recipient of the Extraordinary Doctorate Prize of the Universidad Politecnica de Madrid in 1992 and is a Member of the Editorial Board of Fiber and Integrated Optics, Microwave and Optical Technology Letters, and the International Journal of Optoelectronics. He has also been a Guest Editor for the IEEE JOURNAL OF SELECTED TOPICS IN QUANTUM ELECTRONICS.

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