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Challenges and advances of photonic integrated circuits

Hélène Debrégeas-Sillard *, Christophe Kazmierski

Alcatel-Thales III-V Lab[1] *, Route de Nozay, 91460 Marcoussis, France*

Abstract

The idea of Photonic Integrated Circuits (PICs) appeared in the 1970s, had first achievements in the 1980s with, for example, a laser–modulator. However, recently, due to the demand for increasing bandwidth (100 Gb/s) at lower cost and consumption, and due to semiconductor optoelectronics processing maturity, extremely complex PICs have been developed and industrially produced. This dense integration is an important technological breakthrough, and has a strong impact on optical communication systems with for example cost-effective O/E/O nodes, or transmissions with new modulation formats. This article presents the technological challenges related to PICs, and the major realizations made, up to today. ***To cite this article: H. Debrégeas-Sillard, C. Kazmierski, C. R. Physique 9 (2008).***

Résumé

Enjeux et avancées des circuits photoniques intégrés. L'idée des circuits photoniques intégrés (PICs) apparue dans les années 1970 a connu des premières réalisations à partir des années 1980 avec par exemple le premier laser – modulateur. Mais récemment, en raison d'une part de la demande pour des débits élevés (100 Gb/s) avec des coûts et une consommation toujours plus faibles, et d'autre part de la maturité des procédés de fabrication des composants optoélectroniques semi-conducteurs, des PICs extrêmement complexes sont développés, et produits industriellement. Cette intégration dense représente un saut technologique important, et a un fort impact sur les systèmes de communications optiques avec par exemple la possibilité de nouveaux formats de modulation, ou de nœuds optiques / électroniques / optiques à un coût abordable. Cet article présente les défis technologiques liés aux PICs, et les principales réalisations. ***Pour citer cet article : H. Debrégeas-Sillard, C. Kazmierski, C. R. Physique 9 (2008).***

Keywords: Photonic integrated circuit

Mots-clés : Circuit photonique intégré

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1. Introduction

Optoelectronic components for optical communication applications generally provide one functionality, such as a light source (laser), signal generator (modulator), or signal detector (photodiode).... A Photonic Integrated Circuit (PIC) is the monolithic integration of several functionalities on the same optoelectronic chip, such as a laser integrated with an electro-absorption modulator, a semiconductor amplifier with a photodiode.... It can even lead to

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* Corresponding author.
E-mail address: helene.sillard@3-5lab.fr (H. Debrégeas-Sillard).

[1] Joint lab: 'Bell Labs' and 'Thales Research and Technology'.

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complex optoelectronic circuits, such as multiple modulated sources or receivers, tunable filters, tunable wavelength converters, ...

The idea of integrated optics circuits (now usually named PICs) appeared first in the early 1970s, inspired from the success story of electronic integrated circuits (ICs). It could drastically reduce packaging cost, enhance power budget by suppressing lossy optical couplings, and lower critical power consumption by sharing Peltier coolers among several functionalities.

PICs development progress remained, until recently, below expectations due to several major technological differences and challenges compared to electronics. Firstly, their development was not boosted by volume applications that would have made research, development and manufacturing investments profitable. Secondly, PICs involve the integration of different types of components, whereas electronics concatenate all similar transistors. And thirdly, PICs are not based only on silicon, but on complex technological processes with various specific materials such as Indium Phosphide (InP).

Today, these devices emerge [1] finally because killer applications have appeared. Network operators require larger bandwidth to face ever increasing traffic: while 40 Gb/s systems have just emerged, 100 Gb/s transport migration is already planned within five years. However, at the same time, they require drastic cost per bit reduction. The demand to migrate from 10 to 40 Gb/s with only 2.5 cost multiplication is already difficult to reach, thus for 100 Gb/s, photonic integration seems to be the only way to meet cost requirements and keep the equipment supplier industry viable.

Besides, the expected Fiber-To-The-Home (FTTH) deployment requires low-cost equipment for the customer terminals, where again PICs can play an important role.

At last, PICs can as well address the requirements of network flexibility and wavelength agility, through tunable sources, tunable filters, reconfigurable add and drop multiplexers, ...

Another reason for PICs development today is the maturity of InP processing, which is a key element to reach an acceptable yield, when increasing the size, complexity, and density of optoelectronic chips. New technologies have been developed and are now mastered, which allow conceptions that were not achievable a few years ago. In particular, epitaxy techniques, that are the deposition of thin semiconductor layers, has made huge progress, enabling the growth of different structures on the same wafer. Diffraction gratings by e-beam writing can now provide gratings with any type of tailored pitches.

This article explains the main challenges, configurations and design compromises of PICs. Small-scale integration devices such as laser-modulators, or tunable lasers are presented. Then the recent advances in larger-scale PICs are exposed, such as multiple transmitters/receivers (Tx/Rx), new modulation format Tx/Rx, or complete sub-systems (tunable wavelength converters, tunable transceivers, tunable filters, wavelength selective switches, ...).

2. PICs designs and configurations

Monolithic integration consists in creating several functionalities on the same optoelectronic chip. A common substrate made of indium phosphide (InP) semiconductor crystal is used, and thin layers of semiconductor crystal materials are deposited. They are also composed of elements from columns III and V of Mendeleev's table: Gallium (Ga), Arsenide (As), Phosphorus (P), Aluminium (Al), ... Optical waveguides are then designed by processes of photoresist enduction, lithography, and different etching techniques (chemical or mechanical). The various sections of the device can be electrically isolated by H+ ions implantation, and metal layers are deposited (gold, titanium, platinium) for electrical contacts.

Most components are based on an undoped "intrinsic" semiconductor region sandwiched between p-doped and n-doped InP, corresponding to a p-i-n diode. The undoped layer is made of higher index material such as for example InGaAsP, which confines the optical mode. A current or voltage is applied between top electrodes on the p-side, and substrate on the n-side operating as ground (Fig. 1).

PICs for optical communication applications can integrate many types of functionalities, mainly optical passive waveguiding, optical amplification (gain), signal generation (amplitude or phase modulation), or photodetection. Each functionality has to be realized with a specific material choice, and electrical operation mode.

- *Passive waveguides* require no electrical contact and are made of an intrinsic semiconductor material with a bandgap energy E_g larger than the incident photons energy E_{ph}, making them transparent at the operating wavelength (Fig. 2(a)). They can be mere waveguides to interconnect other devices, or they can be used as coupler or

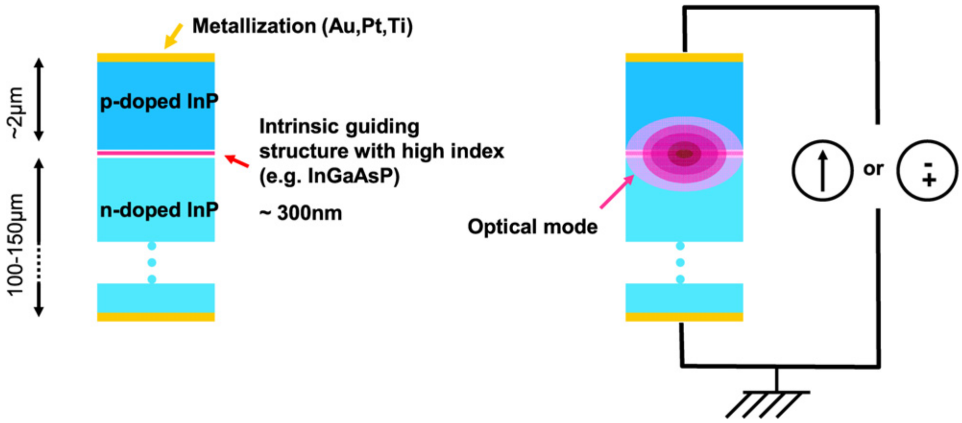


Fig. 1. p-i-n diode operation.

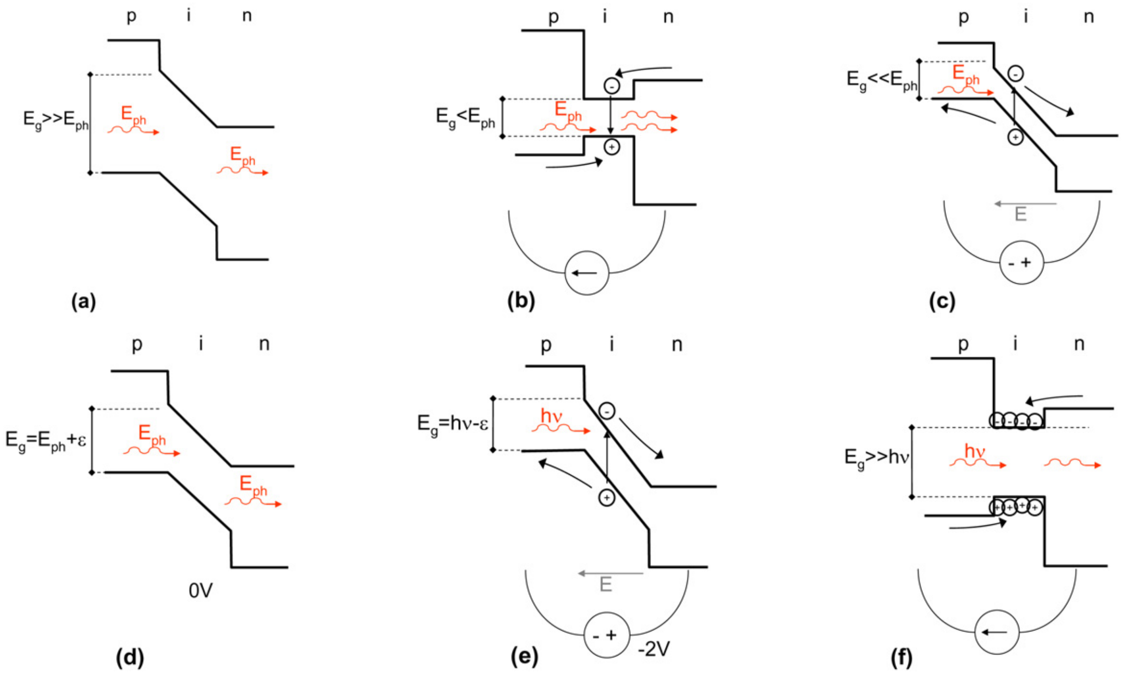
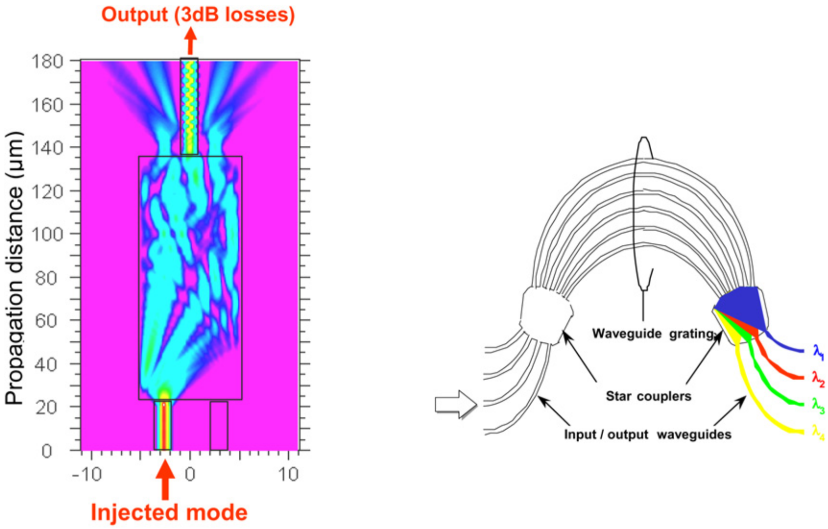


Fig. 2. Band diagram representing the intrinsic material bandgap, and current injection or negative voltage polarization for the various functionalities. (a) passive waveguides, (b) gain sections, (c) photodetectors, (d) electro-absorption modulators at 0 V or −2 V bias, and (e) index or phase modulators (illustration for current injection).

splitter. For example a Multi-Mode Intereferometer (MMI) $N \times M$ is a non-guiding structure with an optimized length, that combines N entries into M outputs by interference effects between multiple modes [2]. An MMI can be used as an M elements divider (MMI $1 \times M$), or as an N to 1 coupler (MMI $N \times 1$, cf Fig. 3(a)).

Another common passive circuit is the *Arrayed Waveguide Grating (AWG)* $M \times N$, with M input and N output waveguides. For example an AWG 4×4 is represented Fig. 3(b). It is made of a star-coupler: a non-guiding section that diffracts the incoming mode, and couples it into K waveguides. The lengths of the waveguides are slightly different, leading to phase shifts at the input of the second star-coupler. Depending on the incoming light wavelength, the K waveguides outputs recombine at different positions of the second star-coupler end facet. Output waveguides at these different spots gather light corresponding to the various wavelengths.

- *Gain sections* are composed of an intrinsic material with E_g close to E_{ph}. When a current is applied, electrons and holes recombine in the intrinsic layer, providing amplification by stimulated emission: one incoming photons



(a) (b)

Fig. 3. (a) MMI 2 × 1, (b) AWG 4 × 4.

generates an additional photon with the same energy (Fig. 2(b)). When the gain section is not limited by reflective elements, light is only amplified by a simple path: it corresponds to a Semiconductor Optical Amplifier (SOA). When the gain section is within reflective facets, a cavity with reduced losses is created, leading to lasing effect. In Distributed FeedBack lasers (DFB), reflectivity is provided by a Bragg grating, that is a periodic variation of the effective index along the waveguide. It operates as a wavelength selective mirror, and generates monomodal lasing effect.

- *Photodetectors* use an intrinsic semiconductor material with E_g way below E_{ph}: incoming photons are absorbed, and generated electrons (resp. holes) are collected in n (resp. p) -doped layers thanks to the electrical field created by applying a negative voltage (Fig. 2(c)).
- Electro-absorption modulator sections use a material with E_g a little higher than E_{ph} at 0 V: the device is then transparent to the incoming photon (Fig. 2(d)). But when applying a negative voltage (typically -2 V), E_g is slightly reduced and becomes smaller than E_{ph}: the device turns absorbing, just as a photodetector (Fig. 2(e)).
- *Devices for index (or phase) modulation* are made with transparent material ($E_g \gg E_{ph}$). The index can be changed by applying a negative voltage (electro-optic effect), such as in Mach–Zehnder modulators, where the differential phase between two parallel waveguides lead to amplitude modulation by destructive or constructive interferences. Index variation can be made even larger by current injection, at the cost of a slower effect (Fig. 2(f)). This configuration is used mainly in tunable lasers, where current injection into a passive section with Bragg grating tunes the maximum reflection wavelength.

A major challenge for PICs is thus the simultaneous optimization of materials for all the required functionalities, and the optimal conditions may be highly contradictory. Firstly, guiding semiconductor bandgap energy E_g needs to by adapted to each section, as detailed above: low E_g for active sections of photodetectors, intermediate E_g for electro-absorption modulation, higher E_g for phase or index modulation, and even higher for passive waveguides.

Secondly, bulk material is preferred for photodiodes where polarization independence is required, or for tuning sections in tunable lasers where optical confinement in the guiding material must be maximum. However, for gain or electro-absorption modulation, structures based on the piling of very thin (a few nanometers) layers called multi-quantum wells are preferred.

Thirdly, the optimum choice of undoped layer, or number of quantum wells may be different in a laser or amplifier section and in a high speed modulator.

To try to adapt the vertical structure to each section, several techniques have been developed by laboratories; the main examples are illustrated Fig. 4. They require extensive epitaxy developments and permanent controls.

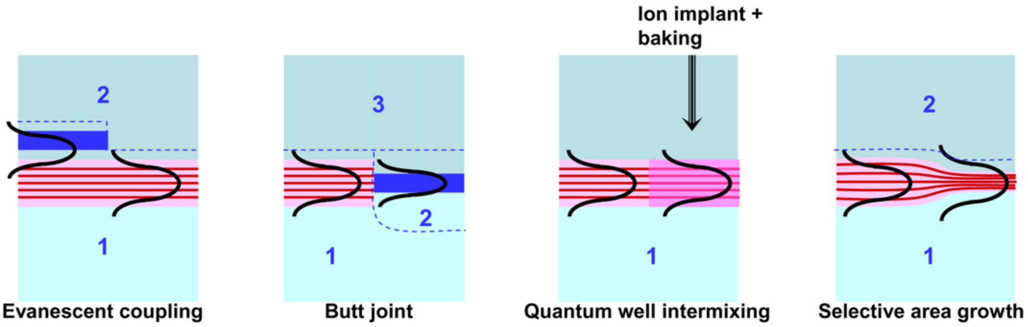


Fig. 4. Vertical structures integration techniques.

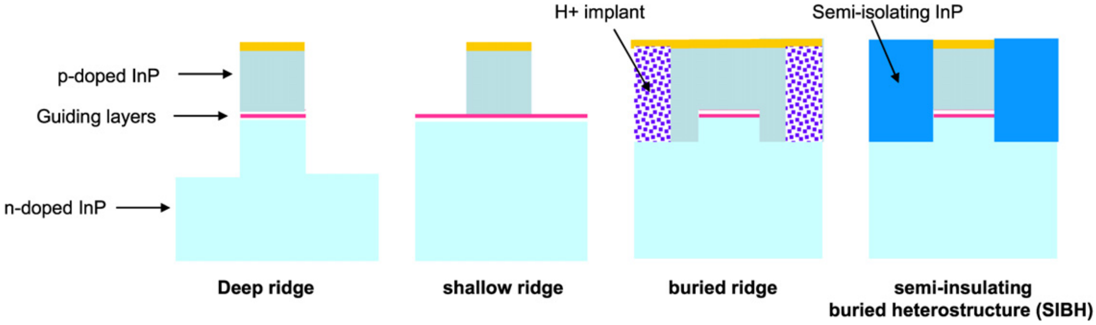


Fig. 5. Principal lateral waveguiding approaches.

The simplest approach is *evanescent coupling*, where the active structure is grown on top of the passive structure. Thicknesses are chosen to confine optical mode in the active structure. Then the upper waveguide is etched in passive section, shifting mode down to the lower waveguide. A *Butt joint* is performed by initially growing one vertical structure, which is then locally etched, and replaced by a second growth other structure.

For *quantum well intermixing* [3], the same quantum wells are deposited over the whole wafer, with top p-doped InP. Then ions are implanted in p-InP, and diffused down to the quantum wells. It generates an intermixing between wells and barriers, leading to controllable band-gap energy modifications.

Selective area growth [4] consists in patterning silica masks on the wafer. During the epitaxy growth, III-V materials do not deposit on silica, and diffuse towards the edges of the mask, slightly differently depending on species. Thickness and composition are thus modified close to the silica masks. By positioning masks with adapted dimensions along the waveguides, one can tailor quantum wells along the device, ranging from transparent material to modulator and active material.

A second challenge for PICs is the choice of lateral waveguiding technologies, that are illustrated in Fig. 5. When integrating a modulator or detector section, waveguiding must be compatible with fast operation, that is to provide a reduced capacitance. When integrating complex passive waveguides, such as, for example AWG, waveguiding with reduced losses and high index contrast is required. Changing the type of waveguide along the device is doable, but at the extent of higher technological complexity, and parasitic reflections at the interface can drastically degrade PICs performances.

Once the optoelectronic chip has been fabricated, diced, and facet coated, it has to be contacted electrically. A standard approach consists in soldering the n-doped facet on an alumina submount with electrical lines, and to use ball-bonded gold wires for p-side connection. However, when the modulation bit rate of the device increases to beyond 40 Gb/s, or when sections with high frequency electrical contacts (modulators or photodiodes) are too far away from the chip side, submount High Frequency (HF) lines need to be brought closer. One solution is to position the submount on top of the chip, right over the HF contacts. Another solution is flip-chip: the chip is soldered upside-down on the submount containing continuous and HF lines, thereby bringing HF signal directly to the chip electrical contact.

When the number of contacts increases, especially HF contacts, electrical crosstalk may degrade performances. It has to be mitigated by a careful design of the chip electrical contacts, and submount HF lines.

Finally, thermal management is one of the main issues for large-scale PICs. A major expected advantage of PICs is the reduction of thermal power consumption by sharing thermal control among many functionalities. However, the densification of devices on the same chip generates important overall heating, and heating between adjacent sections by contamination. Besides, temperature has a strong impact on optoelectronic devices, due on the one hand to semiconductor crystal dilatation generating E_g shift (thereby index, and absorption or gain modification), and, on the other hand, leading to a weaker electrical confinement of injected carriers (electrons and holes) at higher temperature.

One approach is semi-cooled operation, where the PIC is operated at 45 °C to reduce power consumption. Careful design of electrical contacts on the chip, and possibly flip-chip soldering aim at reducing thermal resistance. Advanced packaging concepts are oriented towards thermal dissipation reduction, by bringing temperature control close to the chip, and pushing out heating sources.

Despite all the challenges inherent to PICs, many devices have been developed and are now commercially available. They range from small-scale PICs, such as integrated laser-modulator, or tunable lasers, to large-scale PICs as new modulation formats Tx/Rx, multi-channel Tx/Rx, or even complete sub-systems [5].

3. Small-scale PICs

3.1. Integrated laser-modulator

One of the simplest PICs is a distributed-feedback (DFB) laser integrated with a modulator based on electro-optic or electro-absorption effects which was proposed first in 1987 [6]. Compared to directly modulated lasers, modulation is provided outside the cavity: bandwidth scales to higher values being only related to electrical parasitics RC and/or electrical signal loss in the modulator and its feeding electrodes. Due to a low phase-amplitude coupling of electro-optic and electro-absorption effects, the modulators are less sensitive to dispersion over fibers, and transmission distances are thus significantly increased to ∼1000 km at 2.5 Gb/s and 100 km at 10 Gb/s.

A first approach is based on the phase modulation by electro-optic effects, and two-arm Mach-Zehnder interferometer arrangement is used to convert the phase modulation into amplitude modulation (Fig. 6a). However, to obtain a sufficient extinction with a moderate drive voltage, long interferometer arms in a centimetre range are required. Fast and low-loss Mach–Zehnder modulator structures were recently demonstrated using n-Semi-Isolating (SI) InP-n, SI-n or p-SI-n structures [7]. However, their integration compatibility is still challenging.

A different approach consists in exploitation of strong electro-absorption effects such as Quantum Confinement Stark Effect present in quantum well structures. In that case, an integrated component, Electro-absorption Modulated Laser (EML) has advantage of the compatible guide structure for modulation and lasing functions which can be realized using any of the vertical integration schemes described above. Due to the electro-absorption efficiency, EML may exhibit a large optical amplitude modulation sensitivity 5–15 dB/V. Therefore, this component has an advantage of the lowest drive voltage and an excellent compactness below millimeter range including the laser, enabling higher modulation speeds. However, large absorption changes produce larger sensitivity to fiber dispersion which has to be compensated in a long distance transmission. Therefore, EML component is preferred today in transmission equipment subject to a strong cost competition (metro, LAN, (Very) Short Reach and access).

These two categories of simple PICs have already shown the modulation up to 40 Gb/s and they are competing today for the next transmitter generation with data rate up to 100 Gb/s [8]. Also, more complex integration of both

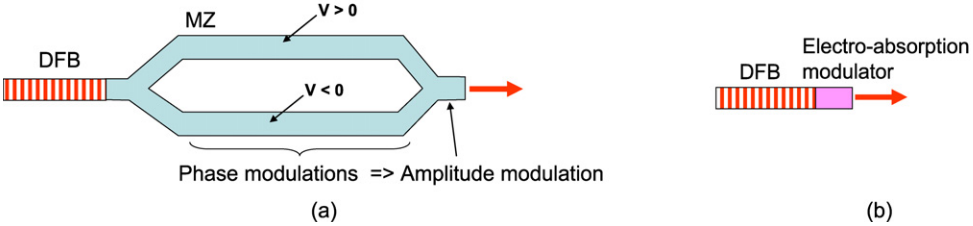


Fig. 6. DFB laser monolithically integrated with (a) a Mach–Zehnder interferometer, (b) an electro-absorption modulator.

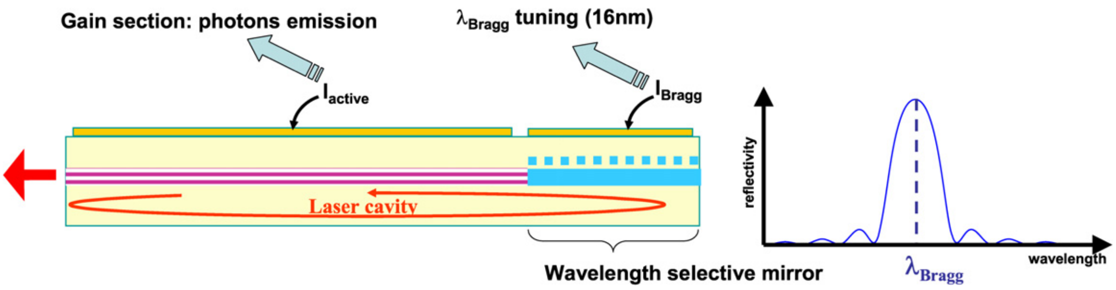


Fig. 7. Scheme of a DBR laser integrating an active section for photons emission, and a passive section with Bragg grating acting as a wavelength selective mirror.

components has been recently attempted by using wavelength tunable lasers instead of fixed DFB wavelength ones providing flexible multi-wavelength data sources [9,10].

3.2. Tunable lasers

Tunable lasers gained huge interest as spare sources in WDM systems to reduce inventory costs, but to provide network wavelength agility as well when integrated in reconfigurable optical add and drop multiplexers. Some non-integrated solutions have been successfully proposed, such as mainly external cavity tunable lasers. But many laboratories focused on monolithically integrated solutions, to limit costly mechanically alignments, and to be compatible with low-cost packaging. Besides, evolution is towards further functionalities integration such as modulation, and fast switching operation based on current injection.

A first for an integrated wavelength tunable laser is the Distributed Bragg Reflector (DBR) laser (Fig. 7), where contrary to DFB lasers, a Bragg grating is etched in a passive section adjacent to the active section. Gain is provided by injecting current in the active section, while current into the Bragg passive section tunes the emission wavelength by as much as 16 nm [11,12].

To cover the whole C+ band (1525–1565 nm), devices with two Bragg sections have been proposed. Thanks to e-beam nano-lithography process, complex gratings can be designed, providing tailorable reflection spectra. Combining the reflection peaks of two gratings, 40 nm tuning is now achieved. Besides, most tunable lasers integrate an output Semiconductor Optical Amplifier (SOA) section, to boost output power up to 13 dBm into the fiber. The most famous such device is Sampled Grating-DBR (Fig. 8(a)) [13], but new devices are competing: Digitally Switchable DBR [14], Y-laser [15], ... However, accurate and complex control loops on multiple interdependent currents are required to ensure stable modal behaviour throughout the lifetime. To overcome this, we proposed a PIC with 3 easy-to-control DBR lasers in parallel coupled into a Multi-mode interferometer and boosted by an output SOA (Fig. 8(b)). Each DBR covers one third of the C+ band, and according to the desired wavelength, only one is turned on, and can be controlled with much simpler loops [16].

Research today is focused on reducing transceivers size and consumption to be compatible with low-cost extended – eXtra Flat Packages (e-XFP) for metropolitan and access networks. Besides, all these solutions are based on current injection tuning, thereby compatible for fast switching (∼100 ns), which could be an important asset for packet switching in future WDM access networks.

Another PIC approach is an array of DFB lasers integrated with a coupler and a booster SOA (Fig. 9(a)) [17]. The DFBs grating pitches are separated by 4 nm, and each DFB can be thermally tuned over its 4 nm range (∼40 °C), leading to 40 nm overall tuning and 13 dBm output power. Control loops are extremely simple, as wavelength depends linearly only on temperature, but tuning is intrinsically slow (a few ms).

Tunable lasers based on an external diffraction grating are now showing excellent performances. They are based on a complex design where a bar of gain sections illuminate a grating with various angles, leading to tunable emission wavelength according to the selected gain waveguide (Fig. 9(b)) [18].

Tunable lasers with SOAs and AWGs have been developed as well since 1994, where the AWG operates as a filter, and the emission wavelength is selected by turning on the SOA corresponding to the desired wavelength (Fig. 10(a)) [19]. Combining two AWGs with slightly different filtering periodicities, larger tuning has been demonstrated (Fig. 10(b)) [20].

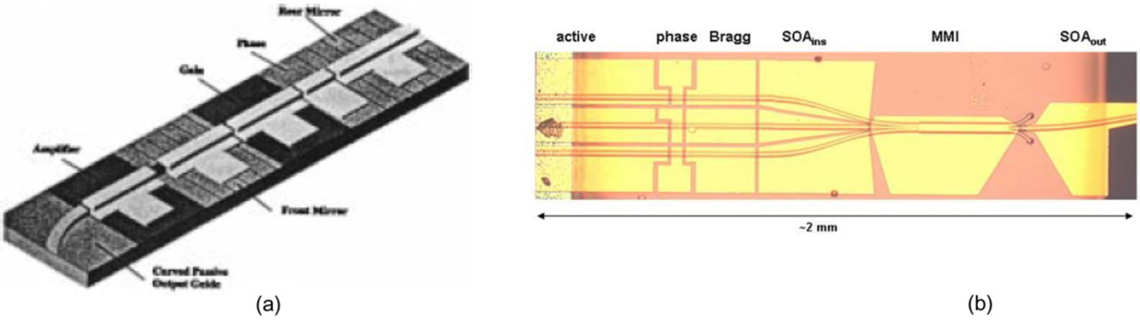


Fig. 8. (a) Sampled Grating DBR (SG-DBR [13]), (b) 3 DBR–MMI–SOA [16].

Fig. 9. (a) DFB array with coupler [17], (b) external diffraction grating tunable laser [18].

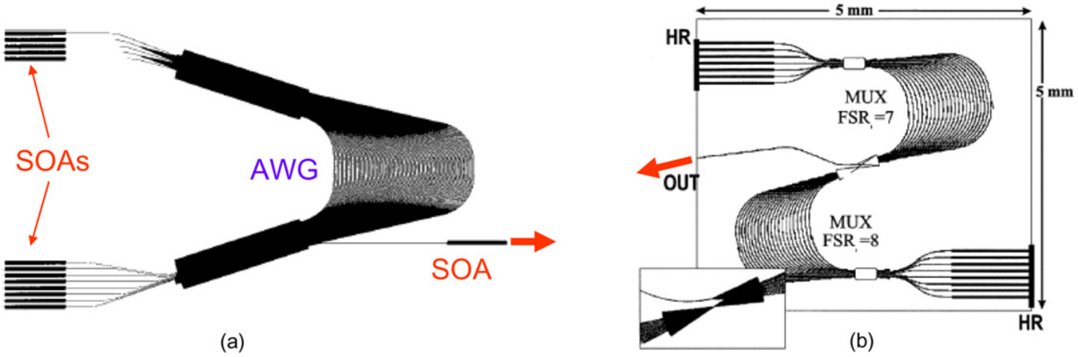


Fig. 10. Tunable laser with (a) one AWG [19], (b) two AWGs [20].

4. Large-scale PICs

Recently, taking advantage of the growing maturity of processes and materials on III-V materials, PICs with a high degree of integration have appeared. They represent a great innovation and industrial challenge, and open the way to new devices and new system operations.

4.1. Multi-channel transmitter/receiver (Tx/Rx)

Multi-channel Tx/Rx integrate on the same InP chip N WDM sources, or N WDM receivers, in order to reduce overall cost and power consumption. However, the challenge is huge because the price of discrete sources is extremely low today due to industrial maturity and volume production. Also, the integration of several modulated sources cou-

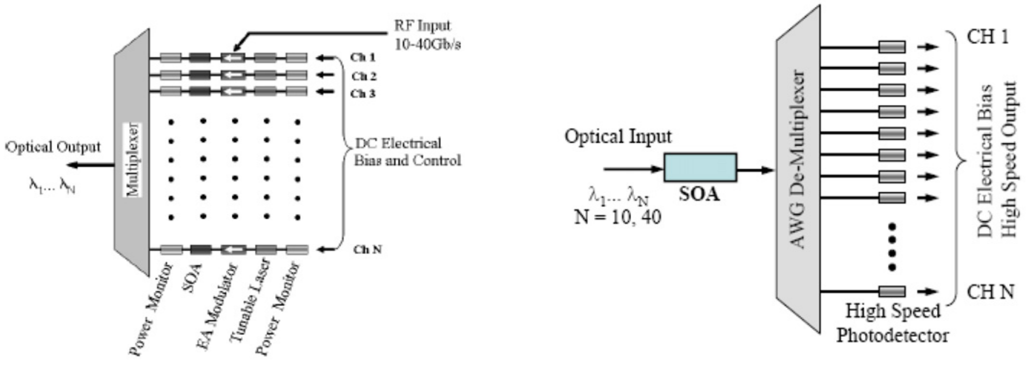


Fig. 11. Infinera's 10 × 10 Gb/s Tx and Rx [22].

pled into one output, or the integration of a demultiplexer and multiple receivers, gather many technological and conception difficulties, and demand perfect process control to reach sufficient yield.

Infinera has been the first company to start the race on such devices, and proposed first 10 × 10 Gb/s Tx/Rx in 2004, as illustrated Fig. 11 [21]. More than 50 functions are integrated on the Tx, composed of 10 sources in parallel including each a rear facet photodiode, a DFB laser with individual thermal tuning, an electro-absorption modulator, a variable optical attenuator, and a $N \times 1$ AWG multiplexer. Electrical contacts are wire-bonded to a submount on top of the chip. The Rx is made of a $1 \times N$ AWG multiplexer integrated with 10 p-i-n photodiodes.

Other laboratories are working today on such approaches, possibly with hybrid solutions where multiplexers are performed on silica waveguides, instead of on the InP chip, in order to increase yield and thereby reduce cost.

By providing sources and receivers at lower price, 10 × 10 Gb/s PICs enable economically viable systems with optics/electronics/optics (O/E/O) conversion, where propagation impairments and routing are managed in electronics in a simpler way [22]. The emergence of these devices may thus have an important impact on overall systems design.

4.2. Multilevel modulation format Tx/Rx

The ongoing trend to upgrade the modulation speed in optical communications (e.g. 40 Gb/s and beyond) leads to growing fibre transmission impairment mitigations (e.g. by fibre dispersion, polarization dispersion, non-linearities, etc.). Also, transmission equipment capacity is reaching now terabit/s range and the fibre spectral bandwidth (tenths of terabit/s) cannot be longer considered as infinite. Even though front-end electronics and signal processing made impressive speed progress last years reaching up to 100 Gb/s, their industrial maturity leads to a high cost.

These three factors create in optical transmission systems an analogous situation as that observed for a number of years in the radio frequency transmission. Therefore, multi-level vector (phase-amplitude) modulation formats, already under broad usage in radio transmissions, become also an attractive and necessary option for optical fibre equipment. Multilevel formats consist of the generation of a multi-bit digital word in a single period of a given clock. Therefore, they have increased spectral efficiency (several bits/Hz) per wavelength over the simplest On-Off Keying. Higher spectral efficiency of the modulated signal at a given speed enables higher fibre transmission capacity and lower signal impairments. Moreover, the front-end electronics may have a significantly reduced speed i.e. a lower cost and better industrial maturity even though additional signal coding and decoding circuitry is also required. Multilevel formats impose however more complex transmitters and receivers which have to be developed for E/O and O/E conversions.

Current transmission experiments with multilevel formats such as Differential Quadratic Phase Shift Keying (DQPSK) are carried out today using a number of bulky $LiNbO_3$ (lithium niobate) modulators and separate laser sources [23]. PIC technology is therefore a very promising way to design cost-effective sources and detectors with reduced size and power consumption. First DQPSK modulators on InP have appeared recently, based on four Mach–Zehnder modulators in parallel. A 10 × 40 Gb/s DQPSK source has been successfully demonstrated recently (Fig. 12) [24].

New designs for DQPSK transmitters using 3 interferometer arms with adjusted splitting ratios, and two electro-absorption modulators have been proposed (Fig. 13(a)) [25]. For DQPSK receivers, solutions could be based on a delay line and a 2 to 4 dephasing interferometer (Fig. 13(b)) [26].

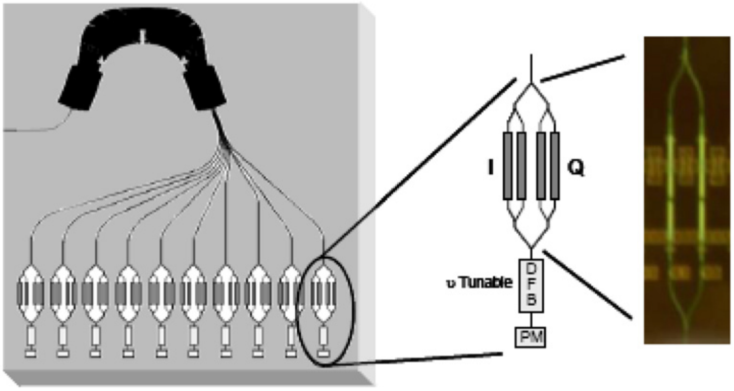
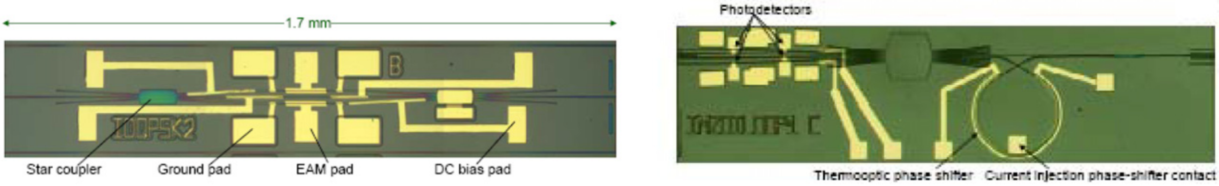


Fig. 12. 10 × 40 Gb/s DQPSK transmitter on InP [25] based on Mach–Zehnders.



(a) (b)

Fig. 13. New designs for DQPSK transmitter (a) [25], and receiver (b) [26].

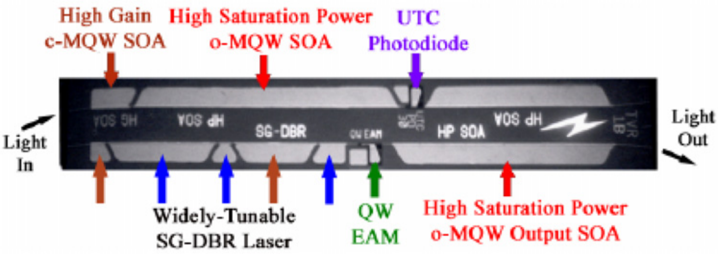


Fig. 14. Sample-grating DBR based tunable transceiver [28].

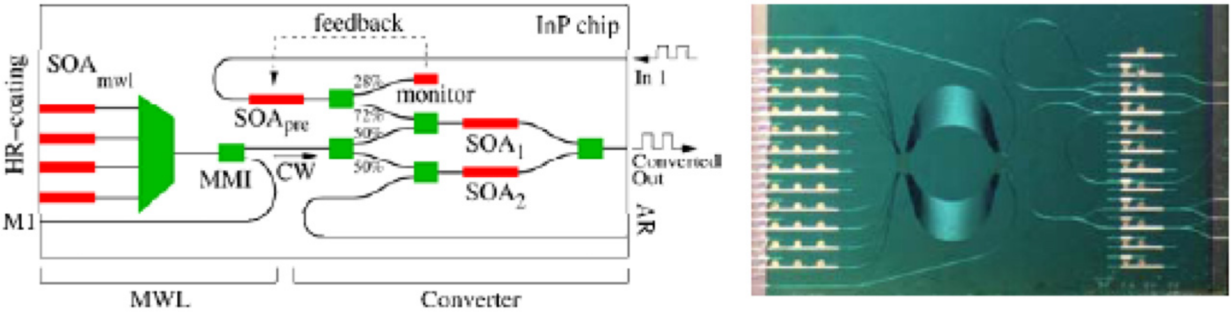


Fig. 15. Tunable wavelength converter using SOAs and AWGs [30].

4.3. *Subsystem PICs*

Mastering PICs technology now even opens the way to complete subsystems, by integrating and designing multiple different functionalities. The list of PIC subsystems is very long, and ever increasing with performance ever improving.

For example, many complex PICs based on a tunable Sampled Grating DBR have been developed by the University of Santa Barbara, such as the tunable wavelength converter [27] or the tunable transceiver (Fig. 14) [28].

Another example are devices using AWGs together with SOAs, that achieve e.g. digitally tunable filters [29], or tunable wavelength converters (Fig. 15) [30].

5. Conclusion

Due to the industrial need for high modulation bandwidth components with reduced cost and power consumption, the maturity of InP based PIC technologies, has progressed quickly during recent years. The first devices with a reduced number of integrated functionalities have opened the way, followed by devices with ever increasing integration levels.

Their development is based on recent huge progress in materials and technological processing. They represent a great boost for photonics industry, enabling higher industrial yield, and enhanced control of electrical and thermal interactions between multiple structures. They represent a new freedom in conception and innovation, making even more complex devices achievable.

Besides, one can expect that PICs will have an impact not only on optoelectronic components industry, but as well on optical communication systems, as they open the way to new architectures (wavelength agile networks, O/E/O cost-effective nodes), and new transmission solutions (new modulation formats).

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