A new approach to laser technology

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A new approach to

A brief review of InP-based photonic integrated circuits (PICs) is given with a specific focus on integrated lasers and amplifiers. A new way of fabrication of PICs called generic integration technology is presented together with selected examples of active integrated circuits, like multi-wavelength laser sources, discretely tunable lasers, WDM transmitters, ring lasers, etc.

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It is well known that the rapid development of integrated electronics, observed in the past decades, started from very simple analog systems, consisting of separate, discrete components, such as resistors, capacitors and transistors. The resulting devices occupied considerable space and were consuming high amounts of electrical power. Also the reliability was a serious problem. The situation changed in 1958 with the advent of monolithically integrated circuits, which revolutionised the way of thinking about electronic circuits. The next major breakthrough was the establishment of the CMOS (Complementary Metal-Oxide-Semiconductor) technology standard. Rapid progress of the CMOS capabilities enabled mass production of functionally advanced and relatively cheap electronic integrated circuits (ICs).

Nowadays, chips integrating even billions of elements are fabricated. The miniaturisation of electronic devices and development of integration technology enabled production of multi-functional, energy-efficient, compact and portable devices, which may be effectively operated with small-size batteries. A good example is the modern cell phone with computational power far higher than early supercomputers. All these factors caused that silicon-based ICs are now ubiquitously applied in every field of technology and everyday life.

A similar trend to miniaturisation and integration is observed in the semiconductor photonics. The rapid development of semiconductor-based photonic devices started with the invention of the light-emitting diode (LED) in 1955 [1] and semiconductor laser diode (LD) operating at room temperature in 1970 [2]. Nowadays LEDs and LDs are key elements in telecommunication, data storage and data processing systems, optical sensors and sensing networks, image processing systems, etc. The progress in semiconductor light sources was accompanied by intensive research and development of other optical components – light modulators, detectors, low-loss waveguides, couplers and (de)multiplexers, Bragg gratings, etc. At present, all of these elements are available in integrated form. A real breakthrough was the invention of the semiconductor optical amplifier (SOA) [3], which enabled both amplification of the optical signals with gain as high as 30 dB [4] and design of various types of integrated semiconductor lasers.

Apart from impressive results obtained up to now in integrated photonics, the choice of an optimal technology is still an open issue. In general, two main approaches are being developed in parallel – the first is based on silicon technologies, while the second is focused on group III-V semiconductors. This work presents InP-based photonic integration technology.

laser technology

InP-based photonics

InP-based compounds manifest excellent electro-optical properties, such as a direct band-gap that allows efficient light generation and detection, light guiding and fast phase modulation. Moreover, the emission wavelength of the ternary (InGaAs, InAlAs) and quaternary (InGaAsP, AlGaInAs) compounds can be tuned over a wide spectral range between 0.92 µm and 1.65 µm [5], depending on the composition of the elements. Simultaneously, the lattice constant can be matched with InP, so that the epitaxial growth of these compounds onto an InP substrate is possible.

Effective integration on a single platform of both passive and active components is a great advantage of the InP-based technology. Invention of the arrayed waveguide grating (AWG) in 1988 [6] started the era of wavelength division multiplexing (WDM) photonic integrated circuits (PICs). The number of components in a single chip was continuously increasing, reaching now several hundreds of components. Examples of already demonstrated large-scale photonic integrated circuits are AWG-based multi-wavelength lasers [7,8], DBR- and DFB-based WDM transmitters [9,10], filtered-feedback WDM lasers [11], mode-locked lasers [12], WDM ring lasers [8], quantum-dot-based lasers for optical coherence tomography [13], tunable lasers with integrated wavelength converters [14], integrated receivers [15], optical time domain multiplexers [16] and many others.

However, even though many InP-based large-scale PICs have been demonstrated already, the commercial success is still limited. Nowadays the market offer covers circuits which integrate relatively small numbers of components. The only truly large-scale PIC, which is commercially available, is the 100 Gb/s transmitter developed by the Infinera Corporation [10], integrating DFB lasers, electro-absorption modulators, power monitors, variable attenuators and AWG multiplexer. At the moment, photonic integration is one of the most promising technologies for fabrication of functionally advanced, compact and cost-effective devices. Generally, PICs, compared to their free-space or fiber-optic equivalents, offer advantageous performance in terms of size and weight, energy consumption, efficiency and reliability. On the other side, they can replace electronic devices, performing the same functionality with a higher operation speed and bit-rate, while consuming less energy. Undoubtedly, the major driver of the development of the photonic ICs is the telecommunication sector. However, these devices have potential applications in other fields, like fiber sensors, medical diagnostics, metrology or switching in photonic interconnects in computer backplanes.

Generic integration technology

In order to achieve the broad application of photonic integrated circuits novel, more efficient fabrication methods are required. One of the most promising solutions is generic integration technology [17]. Its primary assumption is that complicated photonic devices can be divided into basic building blocks (BBs) such as a waveguide, a phase modulator and an amplifier. Additionally, more complex components (e.g. splitters, couplers, filters) as well as whole circuits can be obtained as a combination of these fundamental elements. In order to obtain high yield the technology processes are standardised and general design rules are defined for all designers. In this approach it is crucial to guarantee the performance of every BB by maintaining its characteristic

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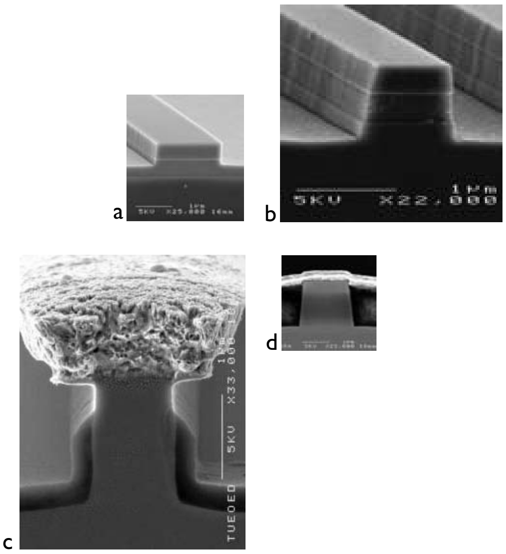

Figure 1. SEM pictures of the basic building blocks of the COBRA process [8,18].
(a) Shallowly-etched waveguide.
(b) Deeply-etched waveguide.
(c) Phase modulator.
(d) Semiconductor optical amplifier.

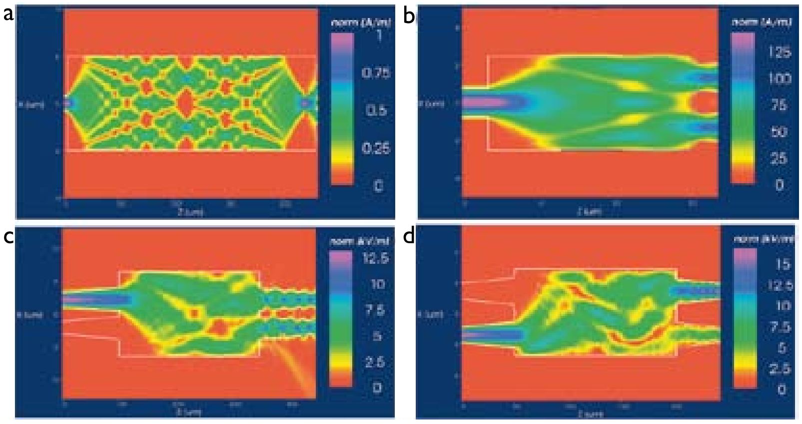

Figure 2. MMI-based components. (Acknowledgement to PhoeniX Software for the licence)
(a) General MMI structure.
(b) 1x2 (3 dB) power splitter.
(c) 2x2 (3 dB) power coupler.
(d) Power splitter with asymmetric (85%:15%) splitting ratio.

parameters, for example attenuation/losses of the waveguides, phase shift in modulators, gain in amplifiers. There is a clear analogy to CMOS, where ICs are designed using transistors, resistors and capacitors, the parameters of which are specified by foundries individually.

The concept of InP-based generic technology in photonics has been developed since 2006 in the JePPIX platform (Joint European Platform for InP-based Photonic Integrated Components and Circuits) [18,19]. The set of basic building blocks for this platform consists of shallowly- and deeply-etched passive waveguides, a waveguide with a top cladding removed for electrical isolation, an electro-optical phase modulator and a semiconductor optical amplifier. Figure 1 presents the SEM pictures of the BBs fabricated in the COBRA Research Institute. By using these basic elements, other composite building blocks can be designed and fabricated. The most important examples of such advanced BBs are presented and discussed below.

MMI-based devices

Among the most commonly used components are the MMI-based (Multi-Mode Interference) devices [20, 21], presented in Figure 2. An MMI section is a piece of a straight waveguide wide enough to support propagation of more than one mode. The principle of operation is based on the cyclic interference of the waveguide modes, due to their different propagation constants. By proper positioning the inputs and outputs of the section, one can design various devices, such as mode filters, 1xN/Nx1 power splitters/combiners, NxM power couplers and splitters with asymmetric splitting ratio [22]. Furthermore, the MMI effect can be used for design of reflectors with a high reflection coefficient [23].

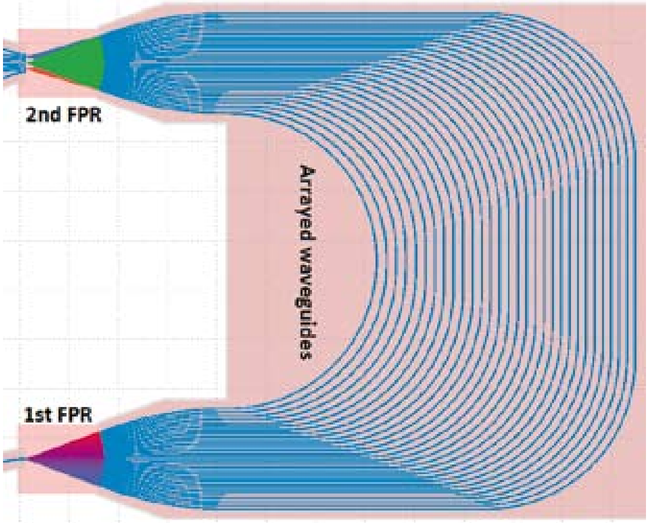

Figure 3. AWG principle of operation: the light is coupled to the arrayed waveguide, phase difference at the output causes tilting of the phase front so that the various wavelength channels are focused in different spatial positions.

AWG Multiplexer

Combination of a slab waveguide and an array of deeply-etched waveguides can form a wavelength (de)multiplexer, called AWG [6,24]. The principle of operation, schematically depicted in Figure 3, is based on introducing a phase difference among the signals propagating through various arms of the array. The optical field at the input diverges in the first free-propagation region (FPR), which is a piece of slab waveguide, and gets coupled to the

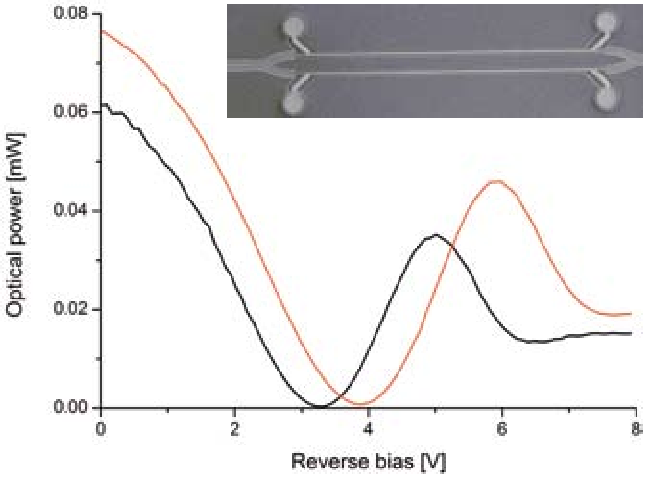

Figure 4. SEM photograph of the Mach-Zehnder modulator and and example of a power transmission characteristic as a function of voltage applied to one of the arms.

arrayed waveguides. The length of each arm is equal to an integer multiple of the central wavelength (λ_c – a parameter of the multiplexer). As a result, the signals carried in λ_c have equal phase at the output of the arrayed waveguides so that this channel is focused in the center of the second FPR. However, other channels are focused in different points, next to the central channel, as their phase front is tilted due to the different lengths of the arrayed waveguides. The AWG provides spatial (de)multiplexing of the WDM signals.

Mach-Zehnder amplitude modulator

Mach-Zehnder amplitude modulators are obtained as a combination of a 3dB power splitter, two phase modulation sections and a power combiner. Figure 4 presents such a structure, together with an example of a static power transmission characteristic. The voltage applied to one of the modulator arms causes a phase change of the optical signal. As the power transmission characteristic has a sinusoidal shape, it is suitable both for digital and analog modulation (while operating in the linear region). Alternatively, instead of combining the two arms with a power coupler, the phase shifter arms may be terminated with reflectors, which would form an amplitude modulator in the Michelson interferometer configuration.

2x2 Switch

When the Mach-Zehnder modulator structure is modified so that splitters/combiners are replaced by 2x2 power couplers, the resulting block acts as a 2x2 integrated optical

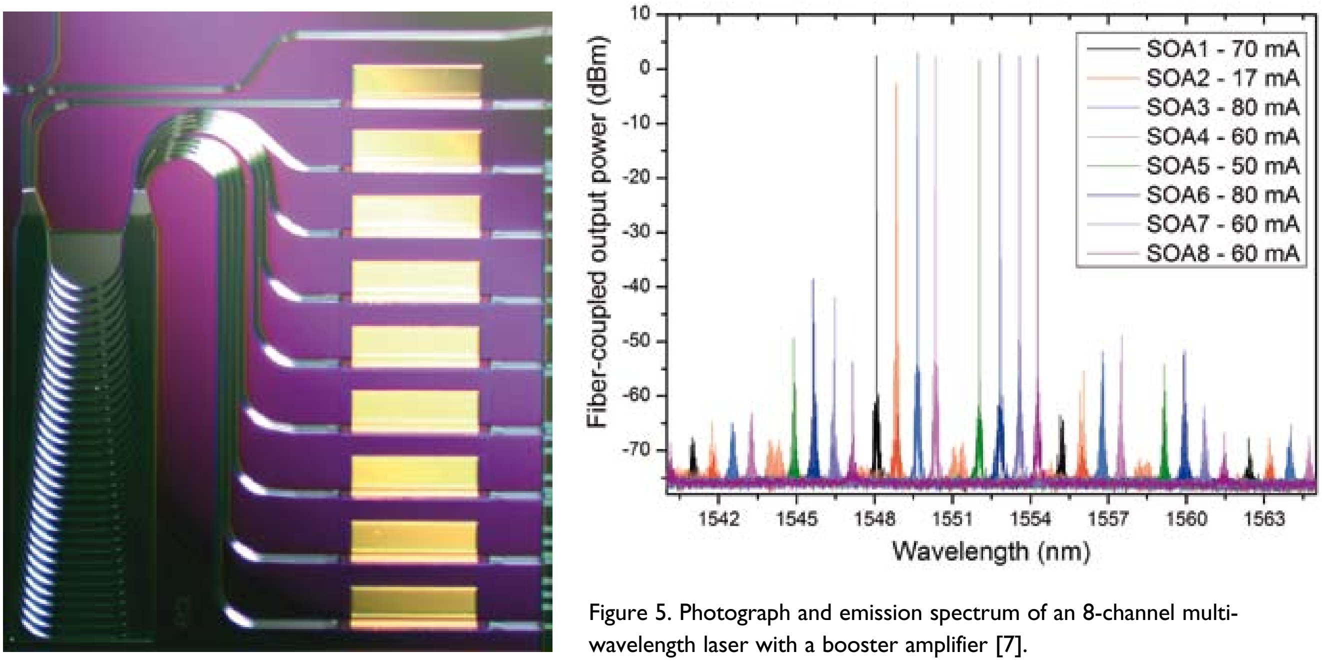

Figure 5. Photograph and emission spectrum of an 8-channel multi-wavelength laser with a booster amplifier [7].

switch. In this case the phase change in one of the arms causes a continuous flow of the power from one output port to another. Under digital modulation with a proper voltage it will discretely switch the signal between the output ports.

Selected examples of ASPICs

One of the most important applications for InP-based PICs are laser sources of different functionalities. Again, the major drivers for the development of such Application Specific PICs (ASPICs) are the WDM telecommunication systems, which require tunable light sources compliant with the ITU grid. Photonic integration helps with providing lasers that can generate several wavelengths simultaneously and can be (discretely) tuned. Such lasers exist in various configurations, described briefly below.

AWG-based WDM lasers

The simplest structure forming a WDM laser source is an array of semiconductor optical amplifiers (SOAs) combined with an output multiplexer [7,8]. The resonator is formed by the Fresnel reflections at the chip-air interface. The AWG acts also as an intra-cavity filter so that the generated wavelengths depend on its passband. The discrete tuning is obtained by turning on and off the selected SOAs. The device can operate both in a single- and a multiple-wavelength mode, depending on the number of simultaneously biased SOAs. Figure 5 presents an example of an 8-channel multi-wavelength laser together with a measured lasing spectrum [7]. An alternative solution is shown in [25]. The gain section is on the other side of the AWG (in the place of the booster), and the SOAs in the array are very short – they are not used to amplify the signal, but as optical gates to turn on and off the individual laser channels.

A more complicated configuration has been proposed in [26]. The resonator is formed by an N_1xN_2 AWG with N_1+N_2 amplifiers (in this specific case, $N_1 = 5$, $N_2 = 8$). As a result forty (N_1xN_2) wavelengths can be generated, depending on which combination of two amplifiers is biased at the same time.

Ring lasers

AWG-based lasers may also operate in a ring resonator architecture. In [8] a WDM ring laser is described, formed by a 4x4 AWG and four SOAs placed in loops connecting the inputs and outputs of the AWG. The power tapping is done by using two of the arrayed waveguides – one for clockwise and the other for counter-clockwise laser signals.

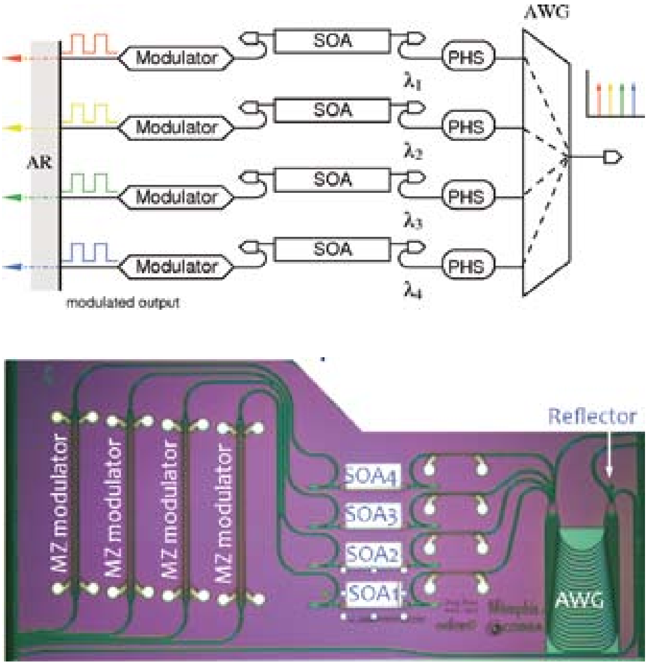

Figure 6. 4-channel, filtered-feedback WDM laser/transmitter [11]. It uses a Fabry-Perot-type resonator with extended cavity, where additional filtering (by AWG) and tuning (by phase shifters) is applied. Mach-Zehnder modulators are for digital signal generation. (Acknowledgement to Jing Zhao for the picture)

Filtered-feedback lasers

A standard Fabry-Perot cavity equipped with some additional components for locking the laser at the specific wavelength, like an AWG and a phase shifter, enables filtered-feedback operation [11]. Figure 6 shows a schematic and a photograph of a filtered-feedback laser. Apart from the laser itself, there are four Mach-Zehnder modulators added for generation of digital signals.

WDM transmitters

The AWG is not the only way of longitudinal laser modes filtering. In the Infinera transmitter chip [10] the operating wavelengths are determined by distributed feedback resonators, while the AWG is a multiplexer combining all

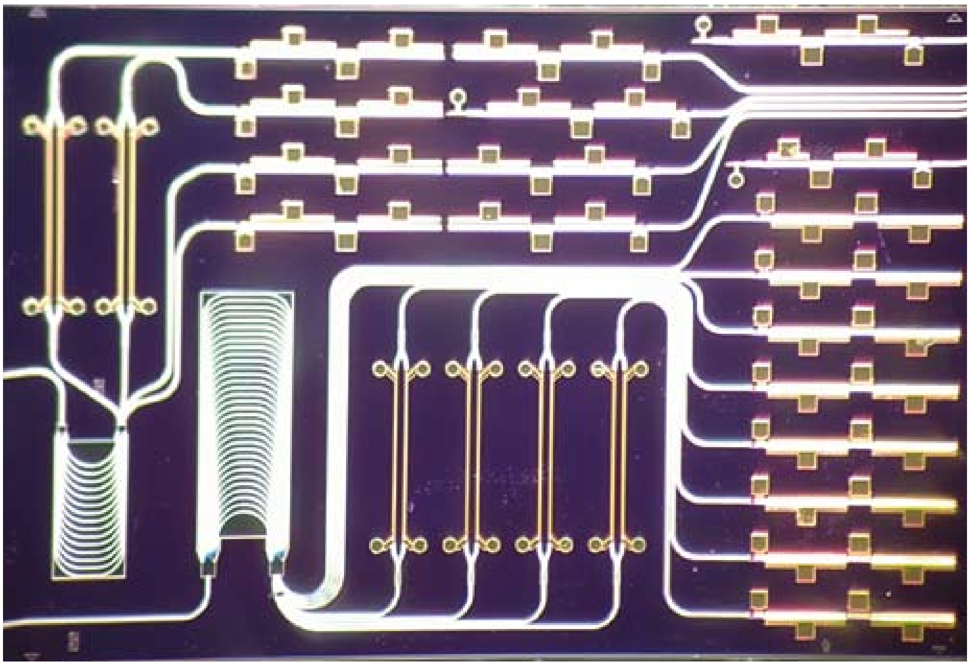

Figure 7. FTTH (fiber-to-the-home) transmitters [9]. The 8-channel circuit comprises an array of eight DBR lasers (right side of the chip). Four channels are digitally modulated by Mach-Zehnder modulators (downstream), four channels provide CW (continuous wave) power for the upstream signals.

ten channels to a single output. A similar approach has been applied in [9]. However, in this case the lasers are built with SOAs and tunable Bragg gratings. Figure 7 presents a chip that has such transmitters implemented.

Summary

Photonic integrated circuits are definitely one of the most promising solutions for the next generation of optoelectronic devices. Their main advantages are the same as for electronic ICs – compact size, energy efficiency, high-speed operation and low-cost large-scale fabrication. In recent years the fabrication technology of InP-based devices has been significantly developed and nowadays chips consisting of hundreds of elements can be produced. However, lack of a standard fabrication and packaging technology still hampers the commercial application of PICs. In comparison to microelectronics, integrated photonics has not yet penetrated the commercial market on a large scale. The generic integration concept, being developed and tested by the JePPIX platform may bring a significant technological breakthrough and completely change the state of the photonic market. At present, two large European FP7 (Seventh Framework Programme) projects – EuroPIC [27] and PARADIGM [28], which combine the potential of key European players, are focused on establishing a generic manufacturing chain in InP-based photonics. This requires achievement of several objectives – developing and providing all users with unified building blocks (both basic and composite), developing professional software for simulations of the circuits and mask designing, with implemented tools for design rule checking, and, finally, determining the standard for packaging. Then, the foundries have to provide on-wafer verification of the manufacturing process.

One of the means to provide low-cost access to the technology is a multi-project wafer (MPW) run, which allows reduction of R&D and prototyping costs of novel devices, as the users pay proportionally to the occupied area. This idea has been extensively tested and used in microelectronics [29,30] and is now being applied in photonics [17,18]. First MPW runs have already been performed at Oclaro (UK), the Fraunhofer Heinrich Hertz Institute (Germany), and the COBRA Research Institute.

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