SOA-based Optical Network Components

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Abstract

SOA-based devices provide a family of key components for optical networks, including wavelength conversion, regeneration, space switching and wavelength selection. All these functions require integration of multiple SOAs that calls for efficient combination of monolithic and hybrid integration to reach performances and cost effective solutions. Several examples are presented and discussed.

Introduction

With the fast evolution of traffic demand and the variety of services, advanced WDM networks will have to be extensible and upgradable both in terms of capacity and geographical distances. Flexibility regarding reconfiguration, management, bit rates, formats and traffic is another key feature required for these advanced WDM networks. Intensive research and development are now directed towards reconfigurable nodes with enhanced functionalities as provided by wavelength routing (WR) or wavelength translating (WT) optical cross-connects (OXC). Another step further, which is also matter of intense advanced research today is the introduction of optical packet switching (OPS). In that context, wavelength - translating broadcast-and-select architectures have been proposed for OXC and OPS nodes. The key functions which are required include space switching, wavelength conversion, all-optical regeneration and wavelength filtering [1].

For all these functions, polarisation independence, bit rate transparency (at least up to 10Gb/s, 40Gb/s in the future), low insertion loss, large input power dynamic range, flat wavelength optical response, high extinction ratio, low crosstalk, etc are key component requirements for OXC and OPS nodes. High speed gating is also a key feature for OPS. Last but not least, manufacturability and reliability issues are of great importance. It appears therefore very attractive to develop generic components for both applications. The semiconductor optical amplifier (SOA) constitutes a key building block for space switching matrices by exploiting optical gating, for all-optical wavelength conversion by cross-phase modulation in SOAs placed in interferometric structures, for wavelength selectors by optical gating of demultiplexed signals and for 3R regenerators.

The implementation of all these functions necessitates integration of multiple SOAs. To reach performances with cost effective solutions, both monolithic and hybrid integrations are efficiently combined [2]. In particular, large-scale SOA space switches exploiting SOA gate arrays, flip chip mounted on Silica submounts have been demonstrated with a capacity up to 1.28Tb/s [3]. Monolithically integrated SOA-Mach-Zehnder interferometers have been realised and packaged into high performance modules achieving up to 40Gb/s wavelength conversion and optical regeneration [4]. Monolithic integration on InP is attractive to achieve compact devices compatible with mass production. This is illustrated in the monolithic wavelength selector which relies on monolithic integration of phased array wavelength demultiplexers with SOA gate arrays. This arrangement yields to extremely compact devices of 4.6x4.2 mm^2 for a 16-channel wavelength selector [5] and pigtailing complexity is considerably relaxed as this is reduced to one input and one output fibre. However, the required dense electrical interconnection can also benefit from collective flip chip assembly technology.

Efficient combination of monolithic and hybrid integration of SOA-based devices is developed to reach high performance, cost effective solutions for advanced components for all-optical networks. Multi-fibre pigtailing and overall packaging issues are also addressed in this context.

Mach-Zehnder Interferometers

While cross-gain modulation in SOAs provides a very simple scheme for wavelength conversion, its application is quite limited as this technique degrades the extinction ratio of the converted signal. In contrast, cross-phase modulation in SOAs placed in an interferometric structure produces simultaneous wavelength conversion and 2R-regeneration (re-amplification and reshaping). The extinction ratio is therefore enhanced and the noise is also reduced. The Mach-Zehnder interferometer offers in addition full flexibility with up- and down-conversion, as well as conversion to the same wavelength when operating in counter propagation or using co-propagation in the DOMO (dual order mode) configuration [4]. For mechanical stability reasons, these interferometers need to be integrated. In principle, SOAs should be inserted in the arms of a passive Mach-Zehnder. This has been reported by several laboratories, either with active-passive monolithic integration on InP [6, 7] or with hybrid integration of SOAs on a silica submount [8]. A much simpler scheme, the so-called all-active MZ-SOA wherein the entire interferometer structure consists of active SOA waveguides, has however shown extremely attractive features [9]. In terms of technology, the fabrication is similar to SOA's. A tensile strained bulk SCH (Separate Confinement Heterostructure) SOA structure has been chosen for polarisation independence and integrated mode expanders (Figure 2) at the input and output ports facilitate the coupling to fibres whereas tilted facets ensure low reflectivity.

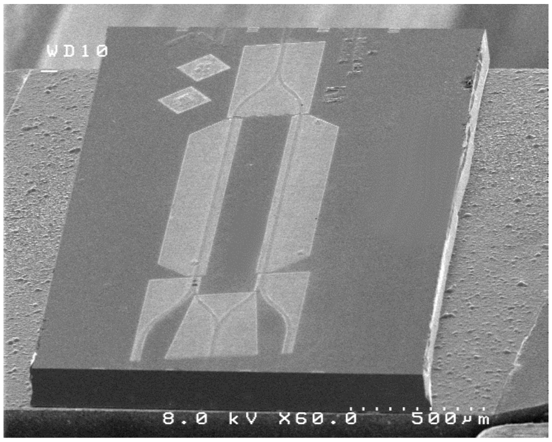


Fig. 1: Photograph of an all-active MZ-SOA all-optical wavelength converter.

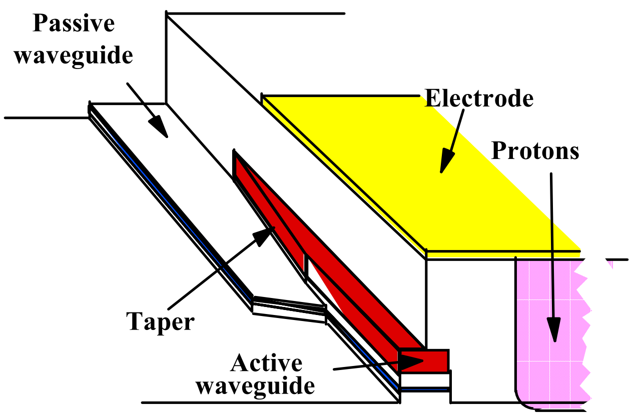


Fig. 2: Integrated mode expander at the output facets of the all-active MZ-SOA based on double-core SCH-SOA waveguide.

The "built-in" peripheral amplifiers (Figure 1) when properly designed [10] allow to get conversion gain and can advantageously be used to provide monitoring sections to enlarge the dynamic range of the device. Hence, the integrated signal pre-amplifier could be used to compensate for input signal power fluctuations. Input powers as low as –10dBm (in fibre) have been reached while pre-amplifier current control allowed an input signal power dynamic range of at least 15dB [9].

The packaging of this device requires complex multi-fibre assembly adapted to tilted SOA stripes and combining CW input polarisation maintaining fibre and standard single mode fibres on input and output converted signals. About 3dB coupling loss is achieved using lensed fibres [11].

Figure 3 shows a schematic view of the module interior; the device heatsink holding the tilted-facet chip soldered with AuSn is mounted on a central Invar block, while the output fibre ribbon, fixed on Si V-grooves and a Si baseplate, is mounted on holders and dynamically aligned before YAG laser welding. The CW input connection is made using a polarisation-maintaining fibre; the fibre axis is pre-oriented on its Invar mount before dynamic alignment and YAG laser welding. The completed module includes a temperature sensor and associated Peltier cooler; overall dimensions are $47x24x15mm^3$.

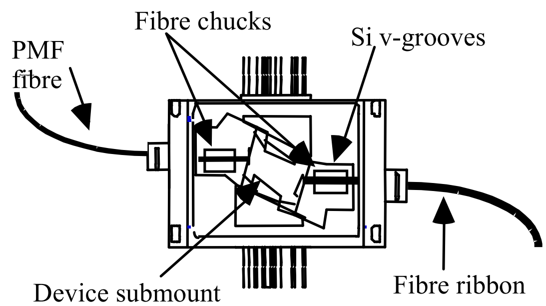


Fig. 3: Schematic view of packaged wavelength converter module [12].

Such module is then mounted on a dedicated electronic control card, together with a CW source laser as shown in figure 4, in the case of wavelength converter boards inserted in the wavelength-translated optical cross-connect nodes demonstrated in the OPEN and PELICAN European projects. Operation in field experiments has been successfully achieved for several months within OPEN [13] and PELICAN [14] field trials demonstrating the stability of the wavelength converter modules.

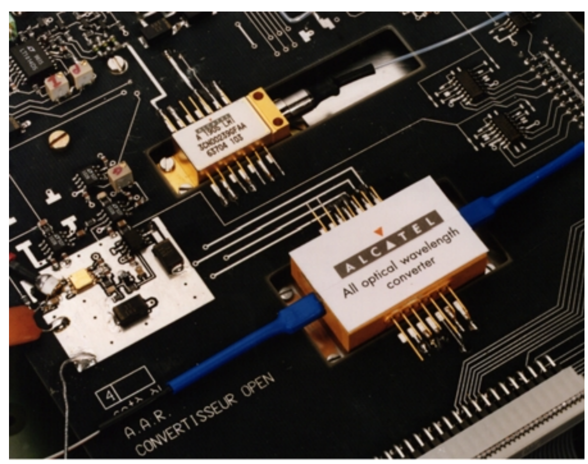
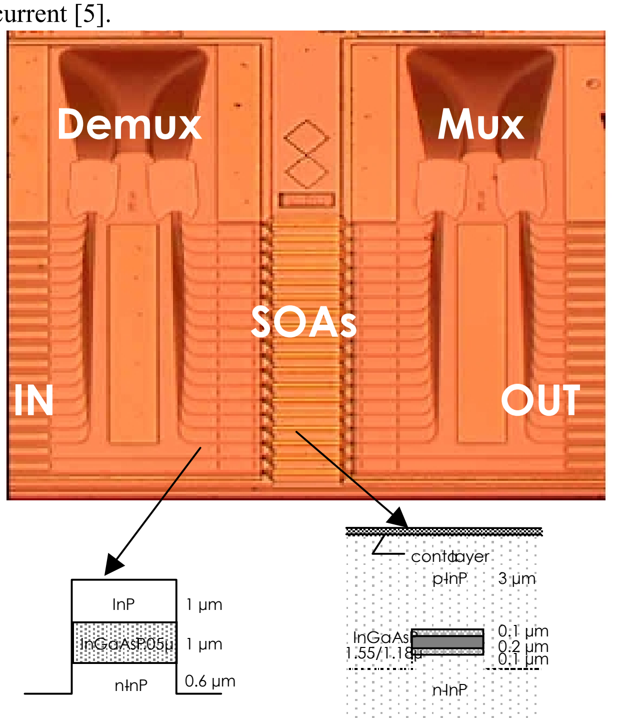


Fig. 4: Photograph of a wavelength converter board.

Even more complex modules have been realised with up to four pigtailed ports in case of differential operation for various 3R-regenerator schemes at 20 and 40Gb/s [15, 16]. In this case the pigtailing has to accommodate a polarisation maintaining fibre in-between two standard SMF on the same side.

InP Wavelength selector

The wavelength selector is composed of two phased array wavelength demultiplexers with SOA-gates in-between. This scheme allows for fast wavelength selection in the ns-range thanks to the fast switching of the SOAs. In contrast to all-optical wavelength converters that can advantageously exploit the simple all-active scheme, an active/passive integration is necessary for the wavelength selector to keep good operation and simple design of the phasars. An active/passive butt-joint integration scheme on InP (Figure 5 & 6) relying on self-aligned buried ridge stripe SOAs and deep ridge passive structures allows for the fabrication of extremely compact devices with uniform coupling efficiency at the active/passive transitions, low propagation loss in the passive sections (~3dB/cm) and low reflectivity at the active-passive transitions [17]. 16-channel wavelength selectors with only 4.6x4.2mm^2 (Figure 5) have been demonstrated with uniform characteristics and zero insertion loss at only 50mA driving current [5].



Passive deep ridge BRS SOA active waveguide

Fig. 5: Photograph of a 16-channel wavelength selector monolithically integrated on InP and schematic structure of the passive deep ridge and BRS active SOA waveguides.

Monolithic integration of wavelength selectors on InP is therefore very attractive in terms of compactness and compatibility with mass production. Also the pigtailing is considerably eased as it is reduced to only one fibre in and one fibre out. In terms of optical performances, quite similar results have been reported on monolithic [5] and hybrid versions [19]. Therefore the choice of the technology will be made on other considerations like yield, manufacturability and cost.

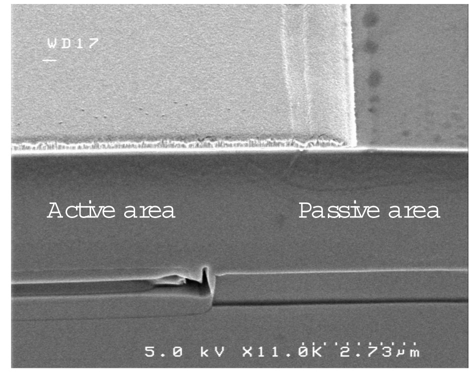


Fig. 6: View of the active/passive butt-joint after MOCVD regrowth.

However, the density of integrated SOAs that need to be electrically connected makes the electrical connections not trivial. Collective flip-chip bonding of these integrated InP chips on host submounts with AuSn bumps is a solution that has been recently demonstrated. Low polarisation-dependency (<2dB) and zero-loss operation at and average value of 65 mA driving current has been achieved with good homogeneity on a 16-channel wavelength selector flip-chip mounted on AlN sumbount [18]. This demonstrates both the potential of InP for large-scale monolithic integration and the absence of noticeable degradation of the performances of the device that might result from flip-chip mounting.

Hybrid integration

Hybrid approach as passive assembly process for optoelectronic chips has been developed, based on silicon submounts with 3D structures and corresponding optoelectronic chips. The flip-chip concept is a low cost and complementary solution to the monolithic integration and allows a high integration level including passive and active devices in the same platform. For example, up to 32-channel wavelength selectors have been reported with hybrid assembly of SOA gate arrays and SiO_2 arrayed waveguide gratings [20].

Basically, the silicon submounts are equipped with mechanical alignment features to ensure precise relative positioning of the fibres and InP chips. V-grooves provide passive alignment of the fibres perpendicular to their optical axis. Their fabrication makes use of the strongly different etching rates of individual crystal planes and transfers the lithographic mask accuracy into structures with sub-µm precision [21].

The position of the optoelectronic chips is defined by mechanical stand-offs and lateral stops (lateral indentations). The dimensions and positions of these features are defined by isotropic and anisotropic etching processes, using self-alignment principles, ensuring the correct relative position to the V-grooves for the fibres.

Bumps of a gold-tin alloy fabricated by electro-plating contact the optoelectronic chip to the electrical lines on the submount. The relative position of bumps and wetting pads on the optoelectronic chip together with the surface tension of the liquid solder provide a small mechanical force, which drives the chip into physical contact with the alignment features of the submount. The lateral accuracy of prealignment does not need to be better than about 10µm but the parallelism control between chip and submount is one of the stringent condition notably in the case of multi-pad chips. Principles of OE chip self-aligned during soldering is described in details in the Figure 7.

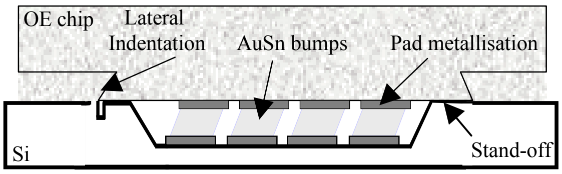


Fig. 7: Principles of OE chip self-alignment

SOA array hybridised on Si

Hybridisation on Silicon or Silica platforms of SOA arrays is very attractive for large-scale fast space switches, as required for fast optical packet switching. This scheme provides a modular and scalable approach, much more flexible than monolithic integration, which complexity would grow with the matrix scale. Hybridisation on 3D structured silicon platform of SOA arrays p-side down has been demonstrated without degradation of the performances of the devices due to the flip-chip assembly. A self-aligned SOA array on silicon submount is presented in Figure 8 containing input and output etched V-grooves to receive the fibres.

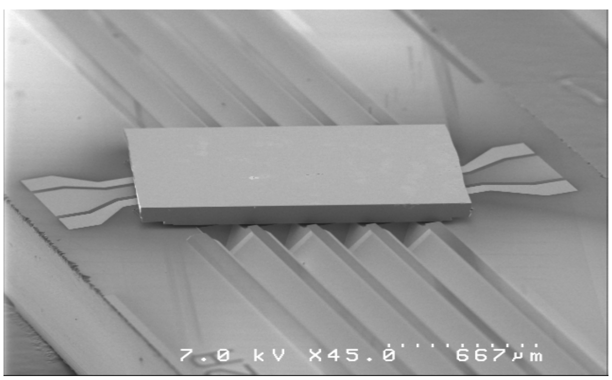


Fig. 8: Photograph of a 4 gates SOA-array hybridised on 3D silicon submount

Two lensed fibre ribbons are placed in the V-grooves and adjusted in only the longitudinal direction to ensure maximum coupling to the SOAs. Passive alignment is achieved in the lateral and vertical directions by pressing the fibres in the V-grooves. Compared to previously reported SOA gate arrays exploiting fibre ribbon dynamic alignment in all directions, this scheme on Silicon submount reduces the pigtailing complexity. The fibre pigtailed 4-SOA array is placed in a small mechanical holder as shown in Figure 9, leading to a very compact sub-assembly ($25x5x3mm^3$). Good optical performances at 200mA driving current and 25°C for a standard SOA structure include fibre-to-fibre gain around 20dB, output power around 7dBm, a noise figure around 12dB, a low polarisation dependence below 1dB and a low gain ripple below 1dB.

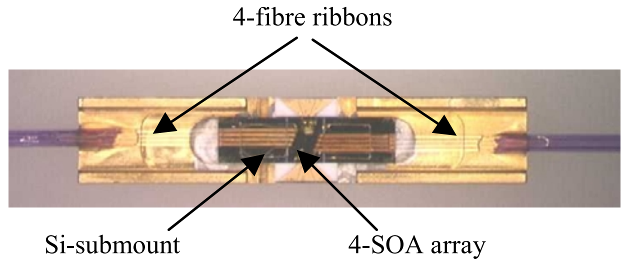
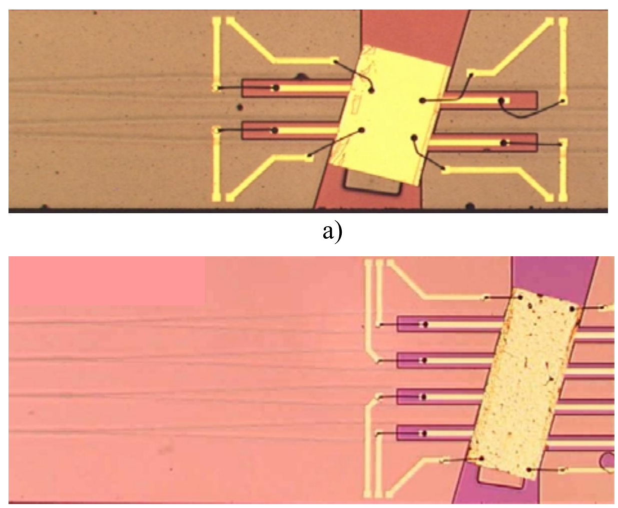


Fig. 9: Photograph of a pigtailed 4-SOA gate array.

SOA array hybridised on SiO_2

Hybridisation on Silicon platforms containing passive SiO_2 waveguide circuits provides another attractive scheme for high functionality devices. This has in particular been reported for wavelength selectors with one platform [19] or with PLC-PLC attachment [20] and for SOA space switch matrices [22, 23, 24]. Developed for WDM routing and packet switching applications, hybridisation of 4 GC-SOA and 8 GC-SOA gate arrays have already been demonstrated on SiO_2/Si submount which integrates 1x4 and 1x8 splitters respectively, electrical interconnections and AuSn bumps for soldering [23,24].



a)

b)

Fig. 10: Photograph of 1x4 space switch with an array of 4 GC-SOA gates (a) and 1x8 space switch based on an array of 8 GC-SOA gates (b).

For the 1x4 space switch, the typical characteristics are: zero insertion loss for all paths at currents above 80mA, fibre to fibre gain homogeneity better than 1.2dB, polarisation sensitivity lower than 0.4dB at 1550nm, 200mA and 25°C. This device compatible with the WDM routing applications has been used in a WDM transmission experiments with 14 WDM channels with a 200GHz spacing at 10Gbit/s. The penalty introduced by this switch was lower than 0.5dB with a 10^{-9} BER in a 10nm spectral range [1550-1560nm].

For the 1x8 space switch, the typical characteristics are: insertion loss lower than 1dB for the best channel and 2.5dB for the worst one at 100mA, polarisation sensitivity lower than 0.7dB at 1550nm, 200mA and 25°C. Test in an 8x8 sub-equipped configuration based on the experimental set-up described in ref. 24 with 16 WDM channels, 200GHz spacing in the range 1535-1559nm, each channel modulated at 10Gbit/s exhibited a penalty in the worst case lower than 1.3dB for a BER at 10^{-9} for a total input power fixed at +4dBm.

These space switch devices, 1x4 and 1x8 configurations, integrating passive and active functions with SOA arrays on SiO_2/Si integrating passive splitters demonstrated attractive characteristics for WDM space switching applications.

Conclusions

SOA is a key element that is used in many devices for all-optical functions of interest for advanced optical networks. These devices require integration of multiple SOAs that can only be achieved by combining efficiently monolithic and hybrid solutions to reach high performance and cost effective solutions. Examples using either monolithic (MZ-SOA, Integrated wavelength selectors) or a combination of both hybrid and monolithic (Monolithic SOA arrays, hybridised on Si or SiO_2 submounts) integration have been illustrated. Very attractive performances have been shown with a quite simple monolithic scheme exploiting the "all-active" integration for MZ-SOA interferometers for all-optical wavelength conversion and regeneration, even in field trial experiments. For 16-channel wavelength selectors, both monolithic active-passive integration on InP [5] and hybrid version with SOA gate arrays and SiO_2 AWGs [19] led to similar optical performances. The choice between the two schemes would then come from size and cost considerations. While it is clear that the monolithic version is much more compact and potentially cost effective thanks to collective process on InP wafers, the processing yield will directly impact the cost. For that reason, "robust" integration process as the one described here are necessary. Monolithic integration is a very powerful technique for integration of same components in arrays as the process remains the same or very close to the one of individual components. This has been illustrated with SOA gate arrays. In this case, the packaging becomes complex and for this reason, self-aligned passive assembly processes have been developed either on Silicon or Silica submounts. Combination of hybrid and monolithic integration of SOAs is creating opportunities for a whole set of devices with enhanced functionalities as required for future all-optical networks.

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