D4.5 Process development and fab run of PI WDM SOAs

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TABLE OF CONTENTS

TABLE OF FIGURES

EXECUTIVE SUMMARY

PASSION introduces new photonic technologies and devices for supporting agile metro networks, capable of enabling target capacities of Tb/s per channel, 100 Tb/s per link and Pb/s per node over increased transport distances in the range of few hundreds of kilometers. The modularity and programmability (via Software Defined Networks: SDN) of the system components of the node is used to achieve the flexibility and agility level demanded by the dynamic traffic, channel bandwidth/path/state/energy requirements of the metro network.

The PASSION switching nodes are designed to function as a reconfigurable add and drop multiplexer (ROADM) within metro core and access network. Implementation of small-footprint and low-power consumption agile wavelength selective switches (WSS) for a node featuring aggregation/disaggregation network functionalities are important criteria. Polarization independent SOAs play a crucial role in the switching node where both polarization are loaded to double the system capacity.

This deliverable document reports the design and simulation of layer stack of polarization independent SOAs with target polarization dependent gain (PDG) less than 3 dB. An indepth literature survey was conducted to identifiy the SOA structures with best performance and high fabrication tolerance in terms of low PDG and high saturation output power. Layer stack of the SOA structures was first designed by optimizing the desired material gain for TE and TM polarizations.

Simulation of the gain properties of two identified structures, that is bulk SOA and a multi-quantum well (MQW) SOA, was done. Both SOAs are 600 μm long and were designed with a ridge waveguide structure which is suited for fabrication and for integration with the rest of the photonic integrated circuits. The simulation results show polarization dependent gain of less than 1 dBs for both bulk SOAs (bias current above 100 mA) and MQW SOAs (bias current above 80mA). In particular, an output saturation power of 12 and 10 dB for TE and TM respectively was obtained for the simulated polarization insensitive bulk SOAs.

Furthermore, characterization of packaged bulk independent SOAs is presented. The measured SOAs is 500 μm and 800 μm long and the measured gain is 9 dB and 20 dB at bias currents of 90 mA. The PDG of these SOAs is shown to decrease with increasing bias current. This happens consistently in both simulation and characterization results.

The presented work serves as preliminary investigation on the design of the layer stack and fabrication of the polarization independent SOAs. Further refining of the simulation method is expected to give more insight to improve the performance of the SOA to be polarization independent for large range of bias currents and input powers. Methods on achieving high saturation output power will also be explored.

1 INTRODUCTION

1.1 BACKGROUND AND MOTIVATION

The PASSION project works towards the development of application driven photonic technologies supporting innovative transceivers and optical nodes featuring different levels of aggregation (in spectrum, and space) for an envisaged network architecture (shown in Fig.1) which is able to match the growing traffic demand in the metro connections. The PASSION approach is capable of establishing high capacity connection for metro network distances (typically few hundreds of km) with high throughput, low-cost, energy-efficient and reduced footprint devices for massive deployment. End-to-end connectivity for novel services and businesses is achieved with dynamic (software defined network) SDN control of the different systems and subsystems to ensure metro connectivity and deployment of services. With the introduction of new modular photonic technology devices, PASSION is capable to reach capacity of Tb/s per channel, 100 Tb/s per link and Pb/s per node.

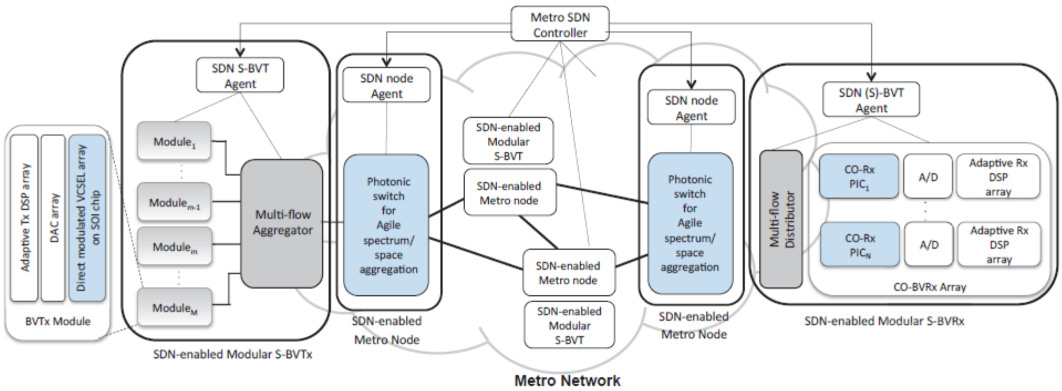


Figure 1 PASSION metro network: envisioned infrastructure, supported by new device technology developments

The growth of internet traffic and particularly bandwidth intensive application such as video, coupled with dynamic and mobile data sources are the driving wheels behind the demand for provisioning of transparent and agile metro networks [1]. To effectively utilize the available spectrum and to allow compatibility with the pre-existing transmission systems, it is very essential to develop a node that can efficiently handle dynamic and growing traffic conditions. Furthermore, it is essential that the nodes are equipped with energy-efficient and small-footprint switching technologies given the increasing energy demands of the global telecommunication infrastructure.

Current state of the art metro networks are quite static and present limited flexibility and scalability. The metro network architecture within PASSION project will be a key enabler of network flexibility and agility required to address cost and efficiency requirements. Increased system flexibility is adopted with sliceable bandwidth/bitrate variable transmitters (S-BVTs) combined with a node featuring traffic aggregation/disaggregation together with switching in space and wavelength. Increase in the capacity is handled with agile aggregation in the spectrum, polarization and space dimensions. This metro network concept will leverage modularity and exploits the SDN paradigm in order to efficiently allocate/use the overall network resources transforming the operation of today's network infrastructure and reducing overprovisioning and margins.

At the metro node, WDM switching enables merging and aggregating/disaggregating tasks on the traffic to maximize resource utilzations by bundling traffic of same destination in a single multi-core fiber (MCF), which are forwarded as bypass traffic in express paths before reaching the destination node in the metro network. The WDM switching is enabled by wavelength selective switches (WSS) which are implemented in a modular fashion to meet the traffic requirements. In PASSION, we propose the exploitation of semiconductor optical amplifier (SOA)-based gate switches monolithically integrated with passive circuitry on InP and/or hybrid integrated with SiPh circuits to support the design of the new metro network architecture featuring functional aggregation/disaggregation at the WSS unit. In addition to the gating functionalities, booster SOAs are used to amplify for compensating on chip losses and achieving low-loss performance. PASSION relies on polarization diversity to double the C-band capacity from 56 Tb/s to 112 Tb/s in a single 7-core fiber. Therefore, developing polarization independent SOA to be embedded in modular WSS PIC units is very crucial. In this deliverable, report design and simulation of epitaxially grown layer stacks of an SOA with low polarization dependent gain (PDG) less than 3 dB, and high output saturation power is presented. Furthermore, the characterization of packaged polarzation insenstive SOAs is compared with the simulation results.

1.2 Target objectives

For the realization of polarization insensitive SOAs, an in-depth literature survey was conducted to identify the SOA structures with optimal polarization independent performance and high output saturation power. Afterwards, two SOA structures are identified based on the performance and the achievable fabrication tolerance. Then, the design of the epitaxially grown layer stack is designed for the two identified SOA structures. The first structure uses *unstrained bulk active region* and the second structure uses *strained multi-quantum well active region*. Furthermore, the simulation results are cross-verified with experimental characterization of polarization insensitive bulk SOAs. The following target objectives are listed:

1. The polarization insensitive performance of unstrained bulk SOA is designed and simulated. The design aims for achieving high output power of the SOA.
2. The polarization insensitive performance of an SOA with tensile-strained multi-quantum well is designed and simulated.
3. The simulation results are cross-verified with experimental characterization of polarization independent SOAs

2 POLARIZATION INDEPENDENT WDM SOAS

2.1 PRINCIPLE OF OPERATION WDM SOAS

To achieve optical gain, an SOA uses an electrically pumped semi-conductor material such that a population inversion occurs between conduction and valence bands. An incoming light wave is amplified when the resulting stimulated emission exceeds losses due to stimulated absorption and other material and structural bands. By appropriately designing the gain material and its bandgap energy, SOAs can be designed to operate in the 1.55 µm communication window. The epitaxial layer stack also determines the polarization type of the light that can be accepted. Moreover, the achievable gain bandwidth of the SOAs supports WDM operation. However, high input power may trigger non-linear effects, which are not desirable when working with WDM systems. SOAs offer advantages as compared to fiber amplifiers in terms of small size and compatibility with photonic integrated circuits (PICs). Their fast dynamics makes them desirable to be used as switching gates.

The principle of operation of a travelling-wave SOA is shown in Fig. 2. An incoming light wave is amplified as it propagates through the waveguide. In a typical SOA the active intrinsically doped gain region is sandwitched between a p-doped and an n-doped cladding layers. The p- and n-doped cladding regions have a larger band gap than the gain middle region. The p-i-n junction is forward biased, resulting in hole (electron) injection from the p-doped (n-doped) cladding into the gain region. Under proper biasing conditions, a population inversion occurs in the active region, a condition which is necessary for the amplification of light. The input signal experiences a single-pass power gain $G=\exp(gL)$, where g is the gain coefficient at the signal wavelength and L is the amplifier length. The amplification process adds broadband noise (spontaneous emission) to the propagating signal caused by spontaneous recombination of conduction band electrons and valence band holes. This noise is subsequently amplified leading to amplified spontaneous emission (ASE). Anti-reflection (AR) coatings are used to suppress reflection at the end-facet reflection.

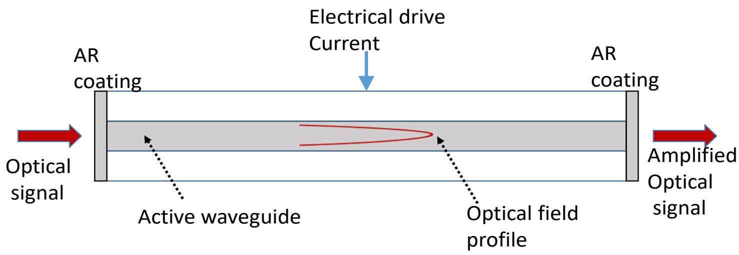


Figure 2 Semiconductor optical amplifier (SOA) basic structure

Depending on the structure of the gain medium, SOAs can have gain sections, *bulk* and *quantum well*, *quantum dot* type (QD) SOAs. Bulk SOAs are known for having a single thick active region [1-4] whereas quantum well (QW) SOAs are equipped with thin layers of alternated wells and barriers in the active region [5]. SOAs that use bulk material require high current densities compared to QW SOAs: in fact, in bulk SOAs the injected carriers move in all three dimensions, while in QW SOAs, the carriers are confined within two dimensions. Quantum dot (QD) SOAs are known for QD nanostructure and have unique gain bandwidth properties that can be finely tuned by changing growth conditions. QD-SOAs can be engineered to offer ultrafast gain recovery, polarization independence, low threshold current [7-9] due to electron and hole confinement in all three dimensions in the quantum dot. However, they require fabrication technique not widely available at the foundries commercially and are not considered within the scope of this deliverable.

2.2 Bulk SOA gain medium

In a bulk material the active region is sandwiched between two separate confinement hetero-structures (SCH) layers, which have a lower refractive index than the active region thereby enabling the light confinement. The active region (core layer) based on intrinsic quaternary Inp (i-InGaAsP) is 100 nm- 500 nm thick. The core layer has lower bandgap than the surrounding cladding layers as shown in Fig. 3.

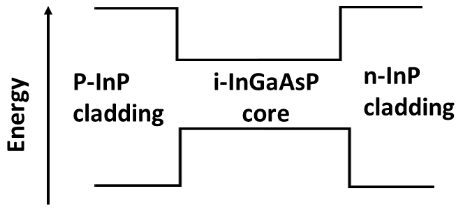


Figure 3 Energy state of a bulk SOA

The p-i-n junctions formed by the p-type and n-type InP layers provide good confinement of the injected carrier in the intrinsic active region. The confinement factor is defined as the fraction of the transverse optical intensity overlapping the active region:

$$\Gamma = \frac{\int_0^d \int_0^w |E(x,y)|^2 dxdy}{\int_{-\infty}^{\infty} \int_{-\infty}^{\infty} |E(x,y)|^2 dxdy} \qquad (1)$$

Where $E(x, y)$ is the optical field, *w* and *d* are the width and the depth of the active region. In general, the confinement factor is polarization dependent. Only a square shaped bulk material can have equal confinement factor for both polarizations, which happens to be difficult to fabricate mainly due to the involved very small size [4]. As a solution, a strained bulk rectangular active layer is used. The confinement factor for the TE polarized light is larger than that for the TM polarized light and this difference is compensated by the tensile strain applied to the active layer [5]. The introduction of the appropriate amount of tensile strain can be used to compensate for the different confinement factors experienced by the waveguide transverse electric (TE) and transverse magnetic (TM) modes.

2.3 Quantum well gain medium

If the active layer thickness is made less than approximately 20 nm, the occupation states available for the confined electrons and holes is no longer continuous but discrete. Such a thin active layer sandwiched between two cladding layers of higher bandgap energy is termed a *quantum wells gain medium*: here the effective active layer is referred as *well layer* and the adjacent cladding layer is usually referred as the *barrier layer*. Fig. 4 shows the energy bandgap diagram of single quantum well (SQW) SOAs, and multiple quantum well (MQW) SOAs. It can be seen that the barriers have higher band gap than the wells. The SQW has poor optical confinement due to the thin active region, however in MQWs, because of multiple quantum wells, the confinement of light is enhanced . A

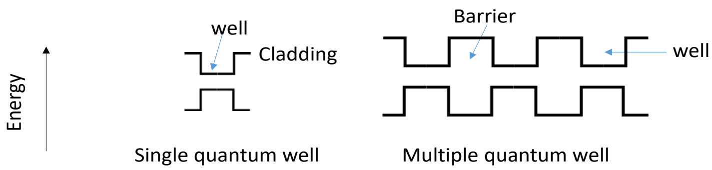


Figure 4 Single quantum well (SQW), Multiple quantum well (MQW) SOAs

MQW SOA can be fabricated by stacking well and barrier layers. The two-dimensional confinement of the optical field creates a bandgap of discrete energy state in QW SOAs compared to continuous energy state in bulk SOAs. These very thin layers can be created using fabrication techniques with high thickness controllability such as molecular beam epitaxy (MBE) and organo-metallic vapour phase epitaxy (OMVPE). Compared to bulk SOAs, quantum well SOAs have wider optical bandwidth and higher saturation output power. However, the gain coefficient of MQW exhibits strong polarization dependency. This is because induced optical transitions from the conduction band to the valence band are much more favorable for TE polarized light (with its electric field parallel to the well layer) compared to TM polarized light (electric field normal to the well layer). If strain is introduced, MQW SOAs can be designed to achieve polarization independent performance.

2.4 Polarization dependent gain

In a MQW or bulk active layer, there are two types of holes: *heavy holes* and *light holes*. Heavy holes are associated with the TE material gain (g_{TE}) and light holes with the TM material gain (g_{TM}). The net gain (*G*) of an SOA is defined as the product of the material gain and the confinement factor. The gain difference between TE and TM polarizations ΔG_{TE-TM} (dB) is expressed as:

$$\Delta G_{TE-TM} = G_{TE} - G_{TM} = \left\{1 - \left(\frac{\Gamma_{TM}}{\Gamma_{TE}}\right)\left(\frac{g_{TM}}{g_{TE}}\right)\right\} G_{TE} \qquad (2)$$

where G_{TE} and G_{TM} are the gains for TE and TM polarizations, respectively, (Γ_{TM}/Γ_{TE}) is the ratio of the respective optical confinements and (g_{TM}/g_{TE}) is the ratio of the respective material gain. Polarization dependent gain of the two orthogonal polarizations in an SOA poses limitation in increasing system capacity by loading both light polarizations. Therefore, efforts to realize polarization independent operation in an SOA is strongly desired and can be addressed via the following directions:

- o By engineering the properties of the material to modify the material gain [2]
- o By engineering the geometry of the waveguides to modify the confinement factor [3]

2.5 Output saturated power level

The output power for which the gain of the SOA reduces by 3 dB from the small signal power is known saturated output power. The saturated power level P_s of an SOA can be defined as [10]:

$$P_s = \frac{1}{a}\frac{dw}{\Gamma}\frac{1}{T_s} \qquad (3)$$

where hv is the photon energy, *d* is the depth of the active layer, *w* is the width of the active layer, T_s is the carrier life time, Γ is the confinement factor, a is the differential gain of the SOA. The saturation output power of optical amplifiers is proportional to the mode cross section, which is expressed as dw/Γ, and is inversely proportional to the differential gain and the carrier lifetime. The saturation output power can be increased by increasing the mode cross section, which can be increased by proper design of the waveguide structure of the active layer. If *a* is large, the gain medium is easy to stimulate with photons. It's very responsive. However, this also makes the gain medium easier to saturate. The differential gain in QW SOA is generally smaller than that of bulk SOA, leading to improved saturation characteristics. The carrier life time, T_s is inversely proportional to carrier density. Therefore, increased carrier density achieved at high bias current leads to high saturation power. On the other hand, the output saturation power can be increased by reducing the optical confinement factor. The confinement factor can be reduced by decreasing the thickness of the active region in case of bulk SOAs and wells in case of MQWs.The impact of decreased confinement factor can be compensated by increasing the length to maintain the gain of the SOA.

3 Literature survey on polarization independent SOA structures

The design and fabrication of polarization insensitive SOAs has been as a topic of research for the past few decades. Thus, a large body of knowledge is available in literature about the design, simulation and fabrication schemes of such SOAs. We have done extensive literature survey of these SOAs to be used for our design and simulation activities. In this section, these works are summarized briefly.

3.1 SOA based on bulk gain medium with square shaped waveguides

In general, the confinement factor for TE and TM polarizations are different. TE polarization confinement factor usually is more than TM because the refractive index change in the normal and parallel direction of the epitaxial layer growth is different. If we use the bulk active layer without any strain, then the material gain for TE and TM is almost the same. Thus, the important factor which makes the difference between the TE and TM net gain is the confinement factor. The use of the square shape bulk active layer removes the asymmetry between between TE and TM confinement factor and make the net gain polarization independent. Fig. 5 shows this comparison.

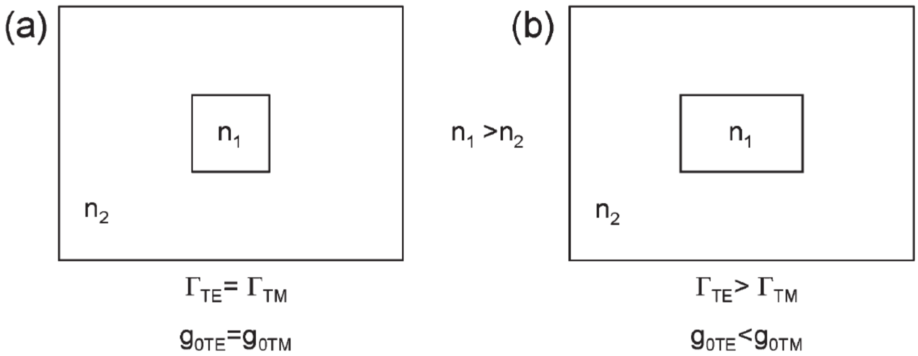


Figure 5 Two schemes for achieving polarization insensitivity, a) square shape structure for which the confinement factor and the material gain are equal, b) rectangular shape waveguide, the material gain compensates the confinement factor imbalance [3]

A polarization insensitive SOA based on square shaped active region of a bulk InGaAsP/InP is demonstrated in [3]. It is based on buried bulk heterostructure which is difficult to fabricate compared to the ridge waveguide structure.

3.2 Unstrained SOA based on bulk gain medium with ridge waveguides

Polarization insensitivity can be achieved by optimizing the structure of the ridge waveguide (by defining the cladding and the core area) so that the TE and TM confinement factor is equal. To minimize the polarization sensitivity, the active layer thickness should be chosen depending on the height of the waveguide and the cladding layers thickness. As shown in Fig.6, the active layer thickness is fixed to 250 nm and the cladding layers thickness is adjusted to 70 nm.

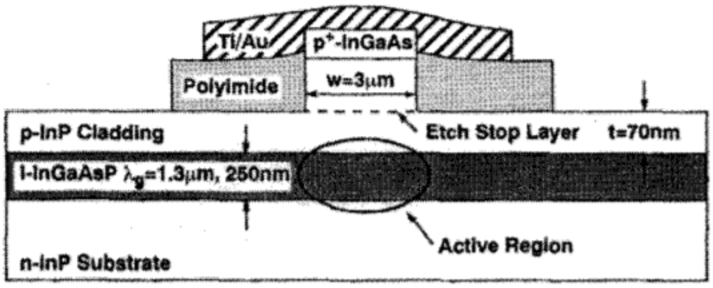


Figure 6 Cross-sectional view of the unstrained bulk PI SOA which requires single step grow [11]

The ridge width is chosen to be around 3 μm to achieve polarization insensitive structure at 1.3 μm operation wavelength. However, this device can be optimized to achieve polarization insensitivity SOA working at 1.55 μm. This can be done by changing the material property so that the result energy bandgap of the active region results gain peak 1.55 μm .

3.3 SOA BASED ON TENSILE STRAINED WITH QW GAIN MEDIUM

For optical signal processing, QW active layers are fascinating alternatives to the bulk active layer. The SOA based on the QW have many advantages including higher saturation power, wide gain bandwidth, ease of integrability with photonic circuits, and fast gain recovery. However, the gain for TE is higher than that of TM. Thus, to achieve polarization insensitive SOA, the energy band of the MQW should be modified by introducing strain in the structure. One way of doing this, is by introducing tensile strain the QWs to enhance the material gain of TM. On the other hand, the confinement factor of the TE polarization always is higher compared to TM. As a result, the net gain could be compromised by using tensile strained QWs. An alternative tensile and compressive strained QWs are used to demonstrate polarization insensitivity [12]. Tensile strain enhances the TM gain and compressive strain enhances the TE gain. The application of tensile strain in some of the wells and compressive strain in the other allows to optimize polarization insensitivity and over all to minimize the overall strain level. In this way the QW epitaxial layer is balanced and can be fabricated.

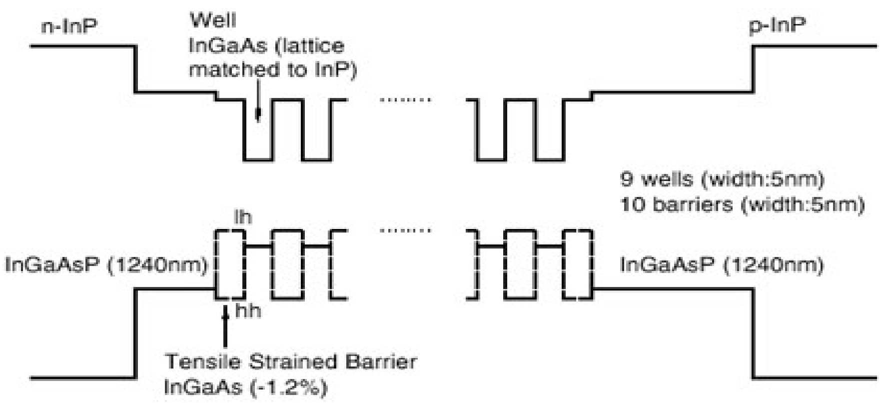


Figure 7 Cross sectional view of the polarization insensitive ridge SOA which requires single step grow [13]

The approach of a tensile-strained-barrier MQW active layer as illustrated in Fig. 7 is very promising for the realization of polarization insensitivity as demonstrated in [13]. The application of the tensile strain in the barrier is used to enhance not only the material gain of TM mode but also the confinement factor. This means thst the confinement factor for the TM mode may be larger than that for the TE mode. In effect, this SOA design enables polarization insensitive performance.

3.4 SOA BASED ON TENSILE STRAINED WITH BULK GAIN MEDIUM

As discussed in section 2, to enhance the polarization insensitivity of the SOA without considering the dimension of the ridge waveguide, one can apply strain on the bulk structure. In fact, using the tensile strained bulk layer enables modifying the valence band for heavy hole and light hole. The heavy hole valence band shifts to the lower levels which enhances the TM gain compared to the TE gain upon application of tensile strain. Therefore, the application of strain is used to modify the material gain of TE and TM modes so that the overall gain is equal for both polarizations.

3.5 COMPARISON OF GAIN MEDIA

In this section, we compare the characteristics of the four type of SOAs which we introduced already. As could be seen from Table.1 the polarization insensitivity of the SOAs are almost in the same range lower than 1 dB. It is important to note that the polarization insensitivity of the strained bulk SOA is the lowest value compared to the other SOAs (0.2 dB).

Table. 1: comparison of the characteristics of four types of polarization insensitive SOAs

Type of SOA / Characteristics	Square cross-section waveguide	Unstrained Ridge waveguide SOA	Tensile strained barrier MQW	Tensile Bulk SOA
Polarization dependency	<1dB	1dB	0.5 dB	0.2 dB
Material	Bulk InGaAsP/InP material	Bulk InGaAsP/InP material	QW InGaAs/InP/InGaAsP material	strain InGaAsP/InP
Working λ (nm)	1550	1300	1550	1550
Tapering	yes	no	no	yes
Saturation power	9 dBm fiber saturation output power @150mA	10 dBm fiber saturation output power @250mA	13-14 dBm @ 200 mA.	17-18 dBm @ 500 mA 13 dBm @ 200 mA
Gain	25 dB @ 15 0mA	27 dB gain @ 250 mA.	27.5 dB @ 200 mA.	19 dB @ 500 mA 13 dB @ 200 mA
Length (μm)	500	500	600	1200
Window region (μm)	25	--	30	--

The active material used in the SOA is summarized in Table.1. The working wavelength for all of the SOAs except from ridge waveguide SOA is 1550 nm. The working wavelength of the ridge waveguide SOA is 1300 nm. It is important to note that we could manage to modify the design of SOA to achieve the function of amplification around 1550 nm.

To increase the efficiency of coupling to the fiber, some of the abovementioned SOAs utilize the tapering region. Tapering could expand the mode volume to ease the coupling to the fiber. Among all SOAs the square shape SOA and tensile bulk SOA uses tapering in their structure.

As indicated in Table.1, the saturation power of the tensile bulk SOA at 500 mA is 18 dBm. This value depends on the bias current so that by decreasing the bias current to 200 mA, the saturation power decreases to 13 dBm. The MQW tensile strained SOA has 13 -14 dBm saturation power at 200 mA. The square shape bulk SOA has 9 dBm saturation power at 150 mA and the ridge waveguide SOA has 10 dBm saturation power at 250 mA. Finally, to decrease the reflection of the facets, square shape and tensile bulk SOA utilize the window region with length of 25 μm and 30 μm respectively. The corresponding length of the SOAs are given in the Table.1. We have selected the two SOA structures in order to be able to achieve polarization independent performance and fabrication tolerance. These structures are *unstrained bulk and strained multi-quantum well SOA* structure both of which is based on ridge waveguide. These simulation results are presented in the next section.

4 Design and simulation of polarization insensitive SOAs

In this section, we present the design of layer stack and simulation of polarization insensitivity for two types of SOAs, namely strained MQW and unstrained bulk SOAs. A ridge waveguide structure is used in both types of SOAs.

4.1 Ridge waveguide structure of an SOA

The schematic representation of a ridge waveguide SOA is shown in Fig. 5. The intrinsic active region active of refractive index of n=3.35 is constituted by 2 µm wide 500 nm thick layer of the InGaAsP/InP layer (with 0.8eV energy gap for quantum well layers). The upper layer is constituted by 1.6 µm P-type InP and the bottom layer is constituted by 1.2 µm n-type InP both of which have refractive Index of n=3.16. The substrate is 200 µm layer of InP. In case of MQW SOA the active region is constituted by several thin layers of wells and barriers (the QWs thickness is 9nm and the barriers thickness is 10nm), whereas in case of bulk SOAs it is constituted by a single layer of 0.5 µm thick active layers.

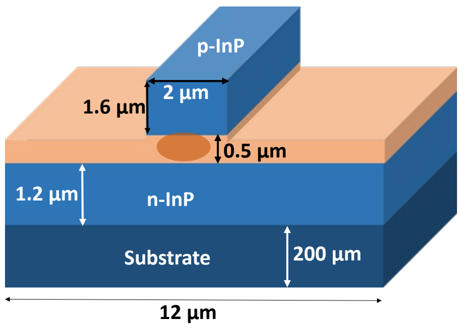


Figure 8 Simulated ridge waveguide structure of an SOA

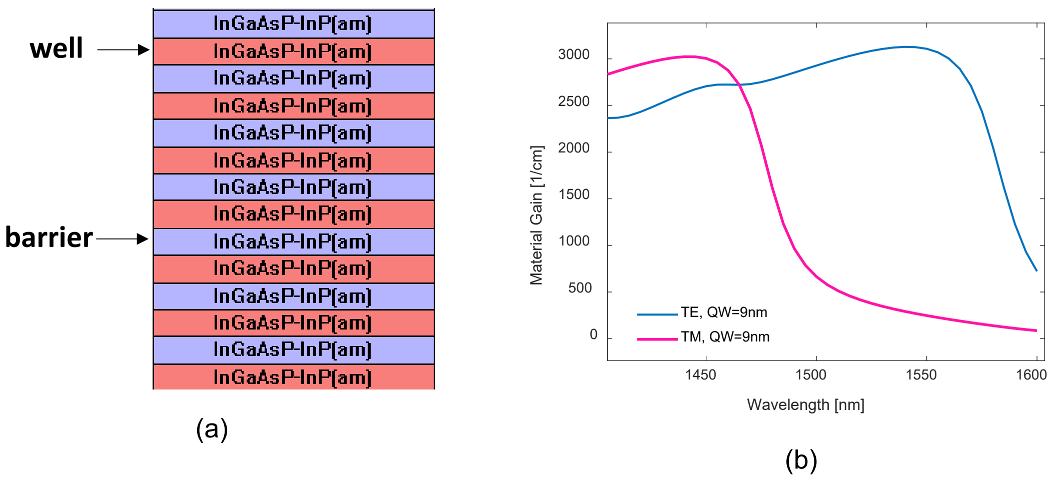


Figure 9 (a) Layer stack of the active region of 7 QW SOA (b) Material gain (TE/TM) for QW=9nm, 7 QWs

4.2 Design of Layer stack for polarization insensitive MQW SOA

As discussed in the previous section, the net gain of an SOA is a product of the confinement factor and the material gain. In unstrained QW SOA, the material gain g_{TE} is larger than g_{TM} because of the property of the band gap structure. Addition of compressive strain enables enhancing the material gain of TE and tensile strain enables enhancing the material gain of TM. Fig. 9(a) shows layer stack of a 7 QW SOA, with 120 nm active region, 2 µm waveguide width. Fig. 9(b) shows material gain per cm at 100 mA for different wavelengths with a compressive strain level of with 1.7 %. It can be seen from the figure that the strain level can be engineered to maximize the gain at 1550 nm for TE, while minimizing it for TM mode. To enable polarization independent operation, tensile strain instead of compressive strain is applied in the QWs as will be explained in the next section.

4.3 Simulation of PI Tensile Strained MQW SOA

The introduction of strain (in QWs) enables the realization of polarization insensitivity by enhancing the material gain for TM. Thus, we can compromise the total gain bearing in mind that the confinement factor is higher for TE polarization compared to the TM polarization. Furthermore, the thickness and the number of the QWs are important. In order to enable polarization insensitivity, in a strained MQW, the following design parameters are critical:

- The number of quantum wells
- The thickness of the wells
- The level of strain

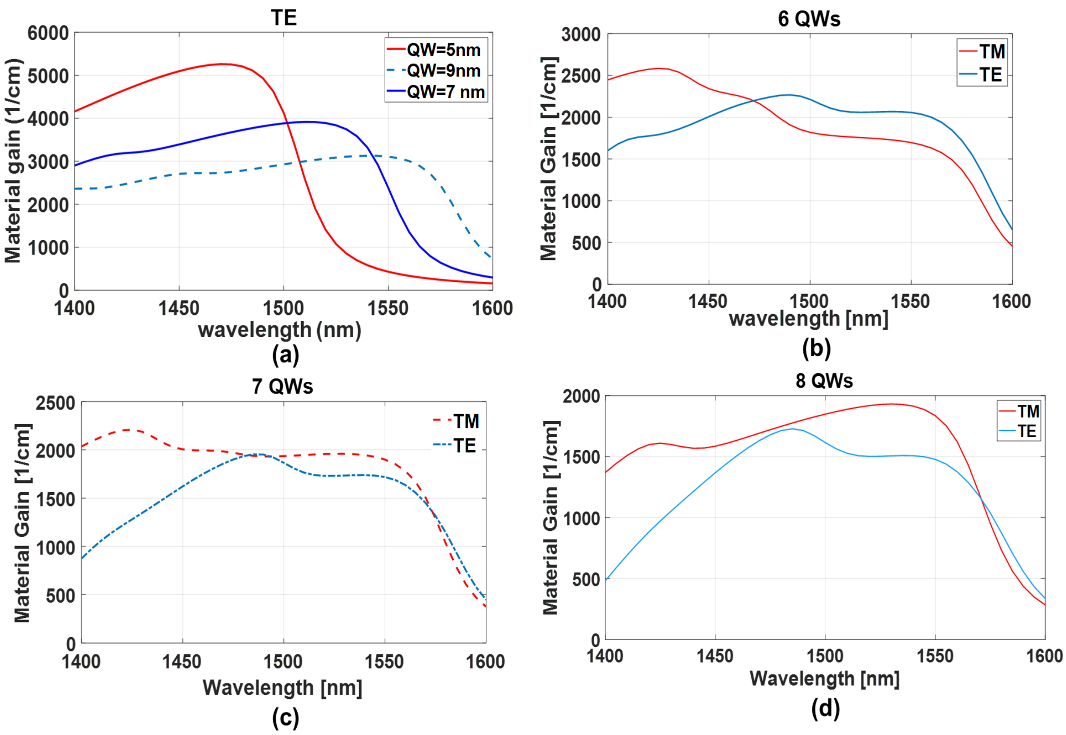


Figure 10 (a) Material gain for TE for 7 QWs with thickness of 5 nm, 7 nm, 9 nm (b) Material gain for TE and TM with 6QW (c) Material gain for TE and TM for 7QW (d) Material gain for TE and TM for 8QW

Fig. 10(a) shows the simulation scenario, in which the width of the quantum well (QW) are varied at 5 nm , 7 nm and 9 nm while the number of QWs is fixed at 7. It can be seen that the material gain profile can be engineered as a function of the QW width. Fig. 10(b), (c) and (d) shows the simulated material gain for TE/TM polarization for 6, 7, and 8 QWs respectively while the QW thickness is fixed at 9 nm. It can be seen that that material gain for TM is lower than that of TE mode for 6 QWs above 1450 nm, while it is higher for 7 and 8 QWs in the wavelength of interest from 1500 – 1600 nm.

Table. 2 shows the level of strain for the cases of 6, 7 and 8 QWs. In cases of 6 QWs, a tensile strain of 0.9 % is applied on the 6 QWs and 4 of the barriers, while compressive strain is applied in the barriers.

Table.2 Simulation parameters for strained MQWs

Number of QWs	*Number Tensile strain in QW*	*Number of barriers*	*Number of compressive strain in barrier*	*Number Tensile Strain in barrier*	*Tensile strain in barrier (%)*	*Tensile strain in QW (%)*	*compressive strain in barrier (%)*
6	6	7	3	4	0.2	0.9	0.7
7	7	8	4	4	0.2	0.9	0.7
8	8	9	4	5	0.2	0.9	0.7

In cases of 7 QW, a tensile strain is applied in 7 QWs and 4 barriers and compressive strain is applied in 4 of the other barriers. In cases of 8 QWs, a tensile strain is applied on the 8 QWs and 5 barriers while compressive strain is applied on the other 5 barriers. The percentage of tensile and compressive strain is given in Table. 2. Then, the net gain of a 600 µm SOA with 7 QWs is simulated, while the tensile strain of 1.19 % is applied on 3 of the QWs and the compressive strain of 1.19 % is applied on 4 of the QWs. The simulation results showing the gain vs the output power is presented in Fig. 11. It can be seen that the PDG varies from 1.2 dB at output power of 2.5 dB and to 4.9 dB at the output power of 12 dBm. The simulation was done at injection current of 100 mA. The

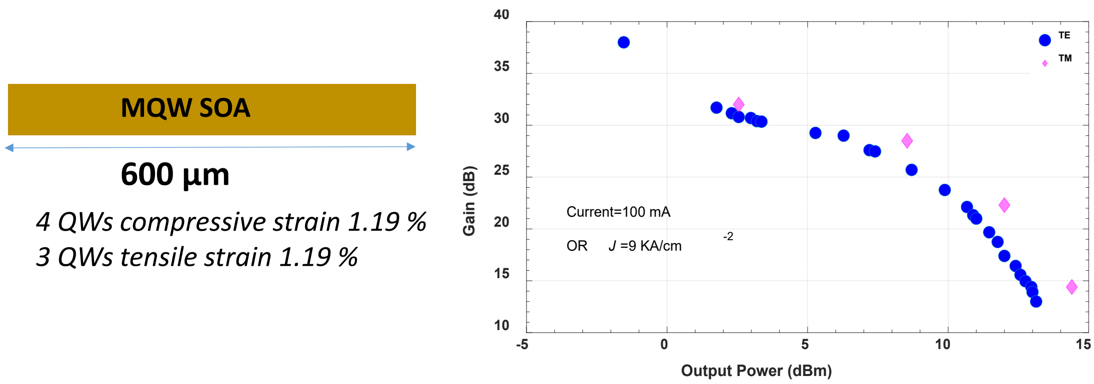


Figure 11 Gain vs output power of a strained MQW SOA, at 100mA injection current for TE and TM polarizations

simulation is repeated for current values ranging from 40-200 mA, while the input power is varied at the values -30 dBm, -20 dBm, -10 dBm. The results are presented in Fig. 12. It can be seen that for input power of -10 dBm shown in Fig. 12(b), the PDG varied from 7.5 dB at 60 mA and to 0 dB at 200 mA. Similar trend is observed for input power of -20 dBm as shown in Fig.12(c). From both plots it is observed that the PDG is less than 3 dB for injection current values higher than 100 mA. This is because the SOA gain saturates for both TE and TM modes. Based on these simulations the saturation power level is around 8 dBm for the QW SOA with 600 µm length. It is important to note that by using asymmetric QWs (with different thickness) it is possible to modify the confinement factor to enhance the saturation output power. Similar trend of decreased PDG is observed for higher injection current for cases of input power level of -30 dBm. It can be seen that at -30 dBm input power the impact of unpolarized automatic stimulated emission (ASE) is more dominant and impacts the PDG to be large. The PDG for input power of -30 dBm, -20 dBm and -10 dBm and current ranges

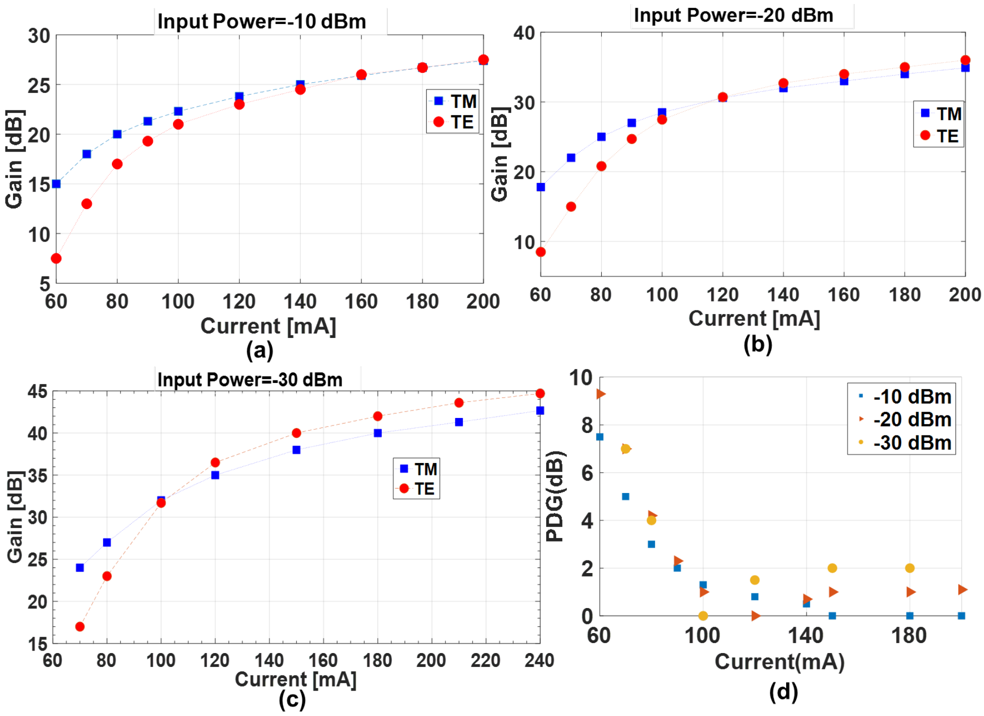


Figure 12 Gain vs current for TM and TE polarizations at input power of (a) -10 dBm (b) -20 dBm (c) -30 dBm (d) PDG comparison

from 60 mA to 240 mA are summarized in Fig. 12(d). It can be seen that the PDG is less than 3 dBs for injection current of 80 mA and higher for input power ranging from -30 dBm to -10 dBm. We have confirmed through theoretical simulations that polarization insensitivity can be completely realized under specific strain levels in the QWs and barrier layers and at specific current range.

4.4 Design of Layer stack of Bulk SOA

As discussed in section 2, in a bulk SOA, there is a single thick layer of active region. In order to achieve polarization insensitivity, we have designed the layer stack of the bulk SOA structure so that the material gain for TM is enhanced with respect to that of TE, so as to compensate the difference in the confinement factor of the two polarizations. After initial modelling and studies, the width *w* of

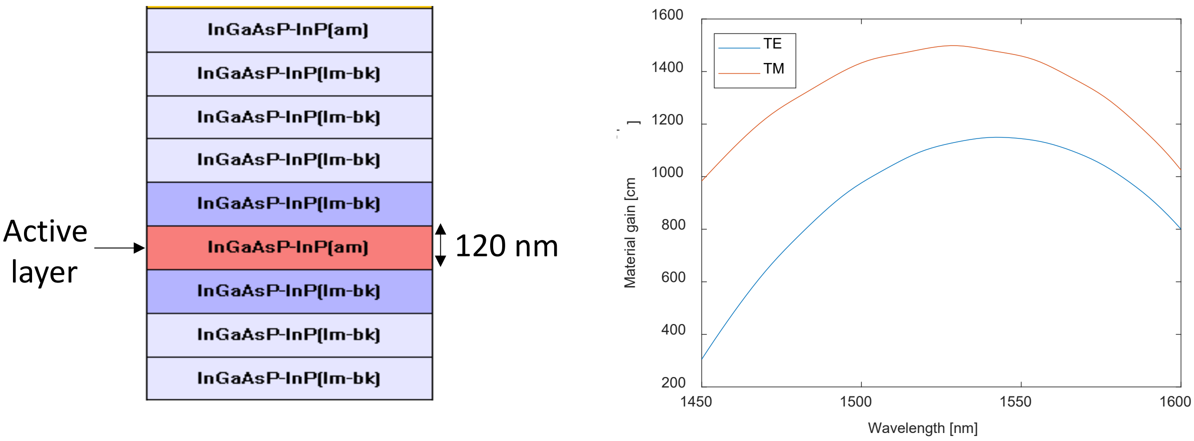
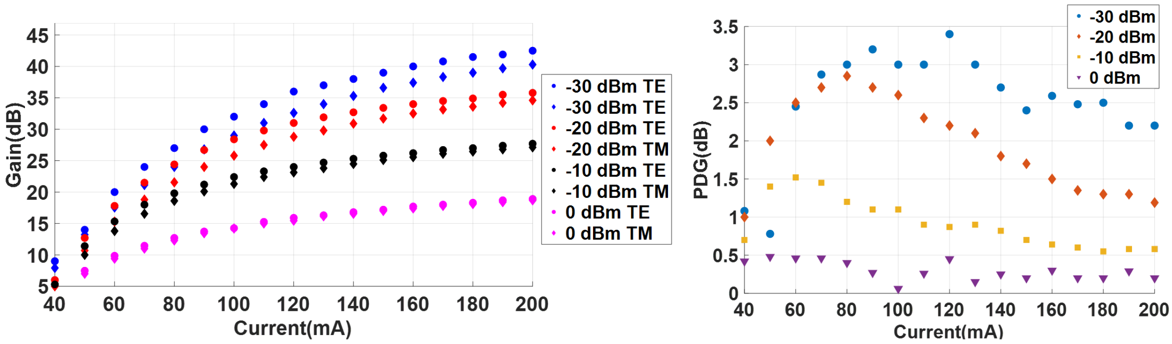


Figure 13 (a) Layer stack of bulk SOA active region (b) Material gain for TE and (c)TM in a bulk SOA the ridge-waveguide and the thickness *t* of the active, and cladding layers were fixed at 2 µm and 120 nm, and 205 nm respectively. The designed layer stack of the bulk SOA structure is shown in Fig.13(a). The simulated material gain for TE and TM mode is shown in Fig. 13(b). When compared for material gain TM, it is observed that the material gain for TM and TE is 1400 cm^{-1} and 1150 cm^{-1} , respectively for biased currents of 200 mA. Thus, this difference in the material gain is used to compensate the difference in confinement factor for the two polarizations so that the overall gain is polarization insensitive. On the other hand, the confinement factor for TE polarization Γ_{TE} is higher than that of TM Γ_{TM} because of the asymmetry of the active layer shape. Thus, by optimizing the geometry of the ridge and layer stack structure, the mode-confinement factors and the material gain are engineered to achieve polarization independent operation.

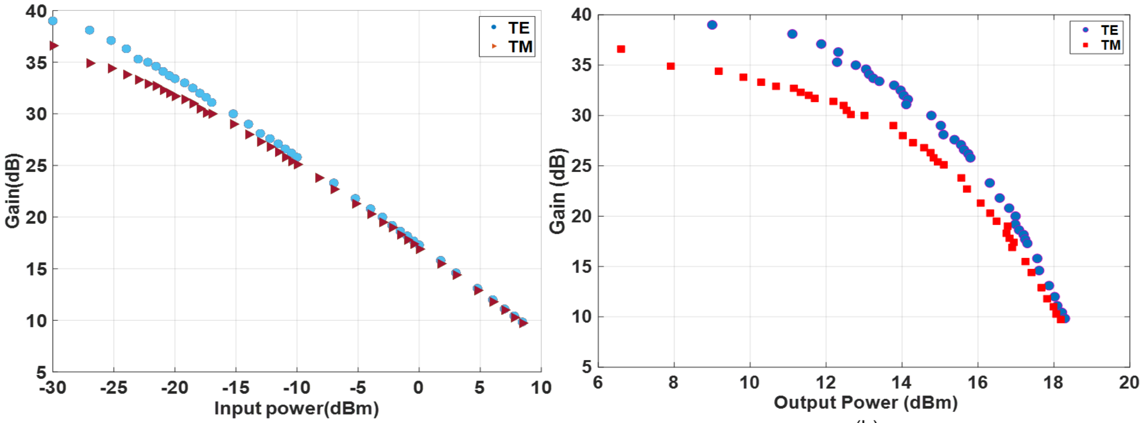
4.5 Simulation of PI unstrained bulk SOA

The polarization independent performance was verified via simulation of a 600 µm bulk SOA and results are given in Fig.14. Plot of the gain for TE and TM polarization, when the injection current is swept from 40 to 200 mA, is given in Fig.14(a), while the input power is fixed at -30 dBm, -20 dBm, -10dBm, and 0 dBm. Fig.14 (b) shows the polarization dependent gain (PDG), there it can be seen than the PDG is less than 3dB in all cases and hence confirming polarization independent performance. The PDG decreases with the increase of the input power and injection current.



(a) (b)

Figure.14 (a) Gain of bulk SOA (dB) vs current (mA) for input powers of -30,-20, -10, 0 dBm (b) Polarization dependent gain (PDG)



(a) (b)

Figure15 Gain of the bulk SOA with respect to (a) input power (dBm) (b) output power (dBm)

Next the gain of the unstrained bulk SOA for both polarizations is plotted with respect to the input and output power level as illustrated in Fig.15(a) and Fig.15(b), respectively. It is evident that by increasing the output power the gain decreases because of the SOA saturation effect. The figure shows that the saturation 3-dB power is around 12 dBm for TE and10 dBm for TM polarized power. The figure also reconfirms that the PDG decreases at high input power since the SOA saturates in high powers.

5 CHARACTERIZATION OF PI WDM SOAS

To understand the performance of polarization independent SOAs, measurement was done on packaged bulk PI SOAs. The measurement setup is shown in Fig.16. The laser light injected into the SOA passes through a polarization controller (PC) which allows to arbitrarily vary the polarization and observe the polarization sensitivity. The output of the SOA is monitored at a power meter or spectrum analyzer. The measured SOAs referred to as SOA-1 and SOA-2 are 500 and 800 µm long respectively.

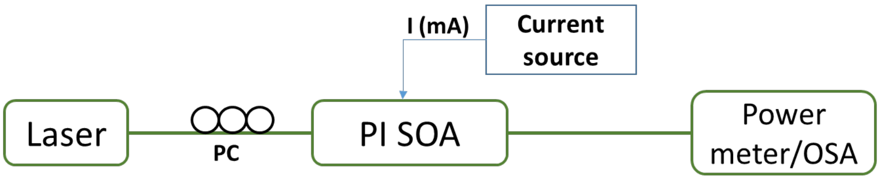


Figure 16 Measurement setup of polarization independent SOAs

5.1 SOA-1

The first measured SOA, SOA-1, has a length of 500 µm. Gain vs injected current is measured for input power of -25 dBm at wavelength of 1562.23 nm. Gain of 9.2 dB is achieved for injection current of 90 mA as can be seen in Fig.17 (a). Further the gain of the SOA with respect to the output power is measured for bias current of 60 mA and 80 mA and is presented in Fig.17(b). The gain profile is enhanced by 4 dB while the bias current is increased from 60 mA to 80 mA. The output saturated power at 60 mA and 80 mA is 0 dBm. Fig. 17(c) shows the gain curve with respect to the input power.

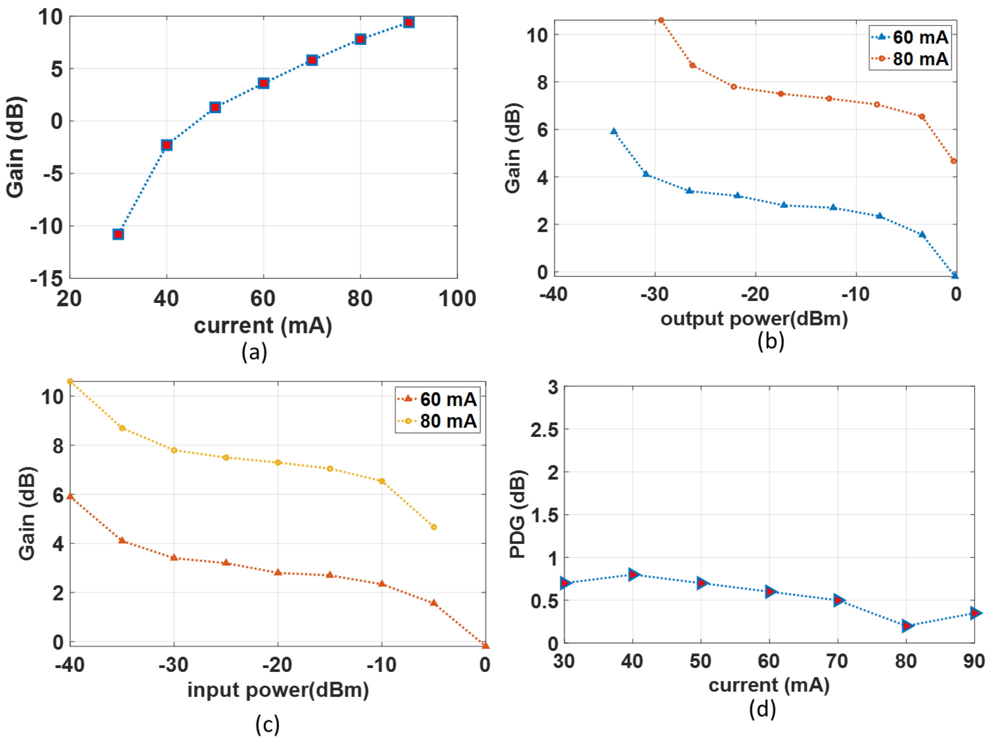


Figure 17 Measurement setup of polarization independent SOA-1 (500 µm) (a) Gain vs current at input power of -30 dBm, (b) Gain vs output power for bias current of 60 mA and 80 mA (c) Gain vs input power for bias current of 60 mA and 80 mA (d) PDG vs bias current at input power of -25 dBm

Then the polarization sensitivity is characterized by arbitrarily changing the polarization controller at the input of the SOA and the resulting gain variation is recorded as polarization dependent gain (PDG) as given in Fig. 17(d). The input power level is fixed at -25 dBm. It can be seen that the PDG is less than 1 dB in all cases. Furthermore, the PDG decreases with increased injection current as was observed in simulation presented in section 4.

5.2 SOA-2

The second SOA (SOA-2) measured has a length of 800 μm. The current injected into the SOA is varied from 30 mA to 90 mA, while the input power is fixed at -30 dBm at wavelength of 1549.12 nm. 20 dB gain is measured for bias current of 80 mA as shown in Fig.18 (a). The variation of the gain vs the output power of the SOA for different bias currents is characterized and is given in Fig. 18(b). The gain curve increases by 7 dB when the bias current is increased from 40 mA to 60 mA. When the current is increased from 60 mA to 80 mA, the gain curve is increased by 4 dB. The saturation output power at 80 mA is 0 dBm. These output power level is suited for 800 μm SOAs to be used as gate switches. The gain curve plotted against the input power is given in Fig. 18(c).

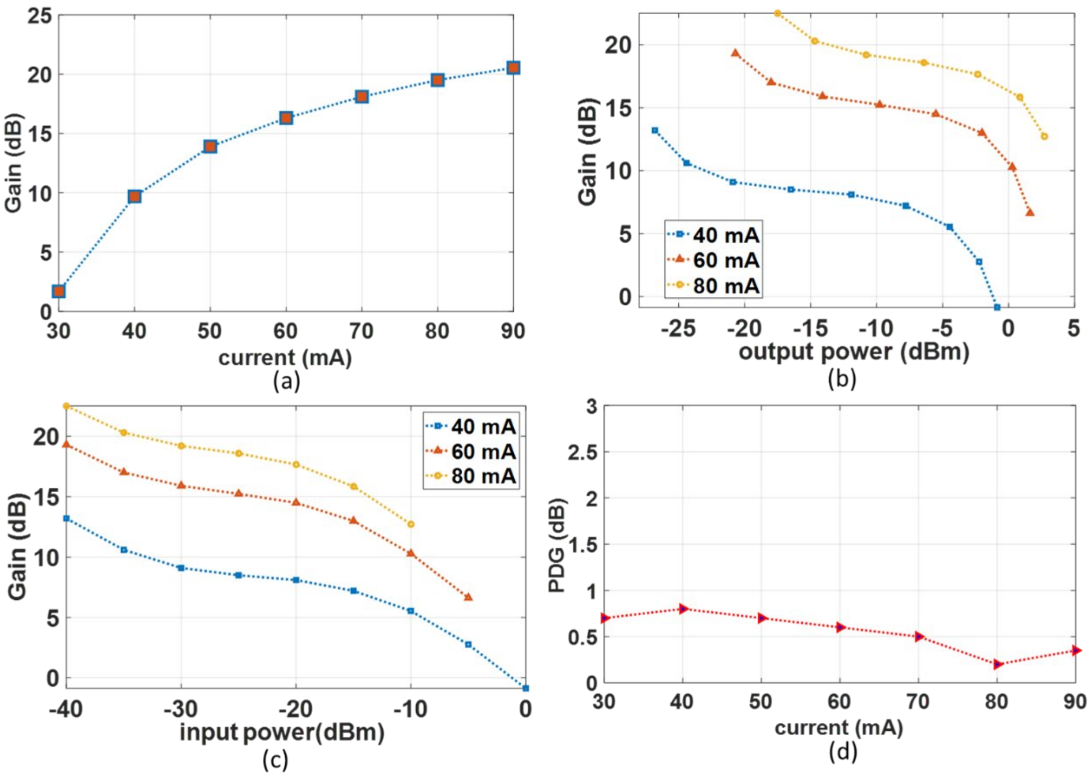


Figure 18 Measurement setup of polarization independent SOA-2 (800 µm) SOAs a) Gain vs current at input power of -30 dBm, (b) Gain vs output power for bias current of 60 mA and 80 mA (c) Gain vs input power for bias current of 60 mA and 80 mA (d) polarization dependent gain (PDG) vs bias current at input power of -25 dBm

Then the polarization sensitivity is characterized by arbitrarily changing the polarization controller at the input of the SOA and the resulting gain variation is recorded as polarization dependent gain (PDG) as given in Fig. 18(d). The input power level is fixed at -30 dBm. It can be seen that the PDG is less than 1 dB in all cases. Furthermore, the PDG shows a general decrease in polarization sensitivity with increase in the bias current. Similarly, the PDG was observed to consistently decrease with increased bias current in the simulation results presented in section 4.

6 CONCLUSIONS

In this deliverable report, the design and simulation of layer stack of polarization independent SOAs with target polarization dependent gain (PDG) less than 3 dB is presented. First, an in depth literature survey was conducted to identify the SOA structures with best performance and fabrication tolerance. Low PDG and high saturation output power are considered as performance metrics. Layer stack of the SOA structures was designed by optimizing the desired material gain for TE and TM polarizations.

Simulation of the gain properties of two identified structures, that are bulk SOA and a multi-quantum well (MQW) SOA, was done. Both SOAs are 600 µm long and were designed with a ridge waveguide structure which is suited for fabrication and integration with the rest of the photonic integrated circuits. The simulation results show PDG of less than 1 dB for bias current above 100 mA for both bulk SOAs and MQW SOAs. The relation of the PDG with respect to the input power was also simulated for input power ranging from -30 dBm to 0 dBm. A decrease in PDG in both bulk and MQW SOAs was observed at increasing input power. Output saturation power of 12 dB and 10 dB is obtained for TE and TM respectively for the simulated polarization insensitive bulk SOAs. Furthermore, characterization of packaged bulk independent SOAs is presented. The measured SOAs were 500 µm and 800 µm long and have a gain of 9 dB and 20 dB at bias currents of 90 mA. The PDG of these SOAs shows decreasing trend with the increase of the bias current. The PDG was observed to consistently decrease with increased bias current for both simulation and characterization results.

The presented results serve as preliminary investigation on the design of the layer stack and fabrication of the polarization independent SOAs. Further refining of the simulation method is expected to give more insight on how to improve the performance of the SOA to be polarization independent for large range of bias currents and input powers. Furthermore, methods on improving the output saturation power will be incorporated.

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