Fabrication Tolerance Study of Polarization-Independent C-Band Bulk SOA for Active-Passive Photonic Integration

Aref Rasoulzadeh Zali, Ripalta Stabile, and Nicola Calabretta
[1]IPI-ECO research institute, Eindhoven University of Technology, Eindhoven, the Netherlands
E-mail: a.rasoulzadehzali@tue.nl

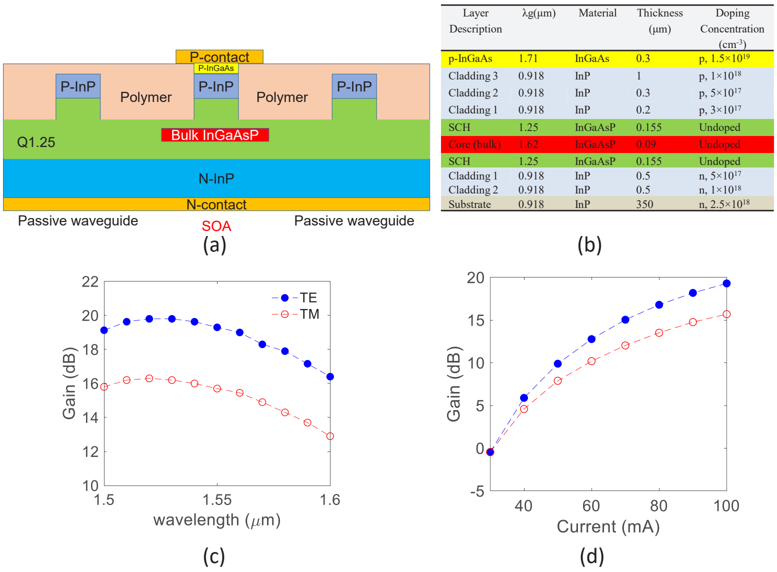
Abstract: *We design low polarization-dependent (< 3.6dB) bulk-SOAs in the C-band suitable for co-integration with passive elements including fabrication tolerance analyses. Optimized design shows SOAs with improve 1dB PDG and the output saturation power of 6.2dBm.*

Keywords: *Integrated photonics, active-passive integration, Semiconductor optical amplifiers (SOA), Bulk active layer, Polarization insensitive SOAs.*

I. INTRODUCTION

Photonic integrated circuits such as transceivers and WDM switches are currently investigated in Datacom optical interconnects as promising solutions to meet the required capacity and efficiently support the steadily growing traffic while reduce power consumption and costs. The required optical power at the receiver side is crucial factor that restrict the number of channels/data rate in transceivers, while the on-chip loss limits the port count scaling of the photonic switch. Consequently, low polarization dependent and monolithically integrated (with passive circuits such as splitter, coupler, filters, etc..) C-band SOA allows fabrication of sophisticated photonic circuits such as WDM receivers and loss-less large port photonic switches based on PI bulk SOA with the required on-chip gain. Several types of polarization insensitive (PI) SOAs based on strained bulk and multi-quantum well (MQW) active layer, as well as square shaped buried bulk structure have been designed and fabricated. However, high precision technologies are needed to grow epitaxial layer with required strain level, to engineer the energy bands [1-4]. Furthermore, heterostructure buried SOAs require high precision lithography process as well as window regions and tapering to improve the facet reflectivity and coupling loss and, respectively which makes the co-integration with passive waveguides challenging.

We have recently demonstrated PI C-band SOA based on bulk active layer in ridge waveguide structure co-integrated with passive elements such as waveguides [2, 3]. In this work we investigate the fabrication tolerance of the PI SOA with appropriate layer-stack suitable for direct passive-active co-integration and its performance such as gain, polarization dependent gain (PDG), and saturation power. The fabrication tolerance analyses is applied to optimal design the PI SOAs co-integrated with the passive waveguide to implement advanced photonic integrated circuits.



Layer Description	λg(μm)	Material	Thickness (μm)	Doping Concentration (cm^{-3})
p-InGaAs	1.71	InGaAs	0.3	p, 1.5×10^{19}
Cladding 3	0.918	InP	1	p, 1×10^{18}
Cladding 2	0.918	InP	0.3	p, 5×10^{17}
Cladding 1	0.918	InP	0.2	p, 3×10^{17}
SCH	1.25	InGaAsP	0.155	Undoped
Core (bulk)	1.62	InGaAsP	0.09	Undoped
SCH	1.25	InGaAsP	0.155	Undoped
Cladding 1	0.918	InP	0.5	n, 5×10^{17}
Cladding 2	0.918	InP	0.5	n, 1×10^{18}
Substrate	0.918	InP	350	n, 2.5×10^{18}

Fig. 1. (a) Cross-sectional and view of the SOA co-integrated with butt-coupled waveguides. (b) SOA layer stack and compositions. (c) Gain spectra at input power -20 dBm and 100 mA bias current for 500 μm SOA. (d) Gain versus current for 500 μm SOA at 1.55 μm.

II. DESIGN AND NUMERICAL INVESTIGATION OF BULK SOA

A schematic of the designed C-band ridge waveguide SOA co-integrated with passive waveguides is shown in Fig. 1(a). The ridge structure confines the light in the middle of the bulk layer, while keeping the mode away from the etched area to minimize the sidewall losses. To optimize the number of modes and waveguide loss, the width of ridge waveguide W is chosen to be 2 µm. The layer stack details are shown in Fig. 1(b). The designed layer stack based on unstrained bulk core layer of Q1.62 InGaAsP (with thickness of 120 nm) surrounded by a Q1.25 cladding, with a total InGaAsP thickness of 500 nm is optimized to minimize possible reflections between passive and active butt-coupled waveguides and simultaneously to achieve low PDG performance. This allows to directly co-integrated the SOA with a passive waveguide layer-stack with exactly the same layers without the bulk layer [2,3]. The designed thickness of the bulk active layer (120 nm) simplifies the fabrication process based on simple single-step grown unstrained active layers, while rendering it polarization insensitive over wide current and wavelength (from C- to L-band) ranges. Moreover, relatively large size of bulk area based on ridge waveguides decreases the model reflectivity without using window region. The PDG is described as $PDG = G_{TE}/G_{TM} = e^{(\Gamma_{TE}g_{TE}-\Gamma_{TM}g_{TM})l}$, Γ is modal confinement factor of TE/TM, α is the material losses, g_m is material gain, and l is the SOA length. As the active layer is bulk, the g_m for TE/TM are almost equal due to the band structure's degeneracy around the bandgap for heavy- and light-hole, and it is self-consistently calculated by solving several equations, including the current continuity, the Poison, the photon rate, the heat flow, and the capture/escape balance equations. Then, the SOA net gain is calculated by solving time-domain traveling wave equations using a slowly varying envelope approximation approach [5]. The modal gain of TE- and TM-mode spectra for 500 µm SOA are shown in Fig. 1 (c) at $J = 10$ kA/cm^2. The gain peak is 19.8 dB around 1530 nm with a PDG of 3.6 dB, while at 1500 nm and 1600 nm the PDG is 3.3 dB and 3.5 dB, respectively. The gain versus current for the same SOA at 1550 nm is shown in Fig. 1 (d). By increasing the bias current, the material gain increases (and the modal gain), which in turn increases the PDG. By increasing the bias current from 30 mA to 100 mA, the PDG increases from 0 dB to 3.6 dB.

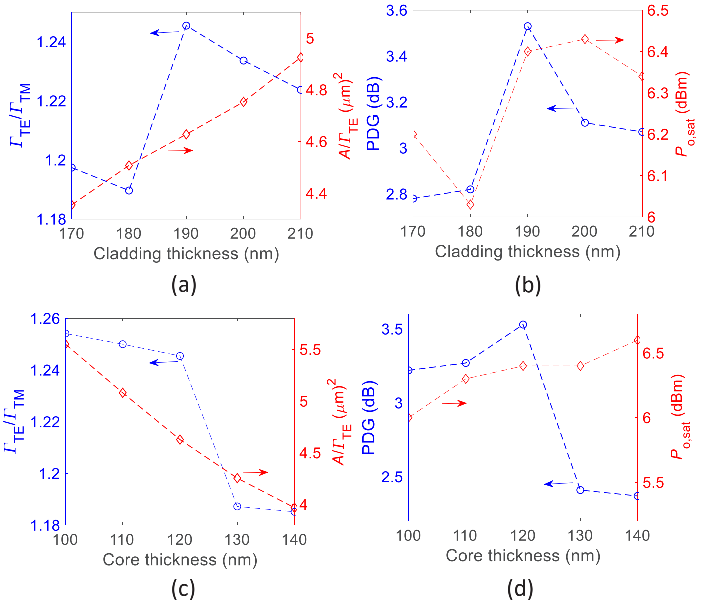


Fig. 2. (a) Simulation of the confinement factor ratio (Γ_{TE}/Γ_{TM}) and A/Γ_{TE} versus (a) the cladding thickness and (c) core thickness. (b), (d) are the corresponding PDG and output saturation power ($P_{o,sat}$) versus (b) cladding thickness, and (d) core thickness all for SOA with 500 µm length biased at J= 10 kA/cm^2 and the wavelength of 1550nm.

The design of an SOA is a complex process that involves optimizing several interlinked parameters. In the context of sensitivity to fabrication tolerance, we focus on the investigation of fabrication tolerance on the SOAs characteristics such as PDG and output saturation power. The fabrication tolerance involves active region thickness tolerance, including core and cladding layer thickness, which depends on the epitaxial growth mechanism and precision. Typical precision of the InP foundries is around ±10%. The active layer thickness influences the confinement factor (Γ) and effective mode area (A) and correspondingly gain, PDG, and output saturation power. Fig. 2(b) shows the PDG variation versus cladding layer (Q1.25) thickness. This figure demonstrates that the PDG varies between 2.8 dB and 3.6 dB as core thickness increases from 170 nm to 210 nm (±10% tolerance precision). This is confirmed by Fig. 2(a), which shows almost the same behavior of confinement factor ratios (Γ_{TE}/Γ_{TM}) values for different core layer thicknesses. Thus, the core layer thickness has limited impact on the PDG. By thinning down the core layer from 210 nm to 170 nm, the effective mode area A to confinement factor (Γ) ratio (A/Γ_{TE}) improves from 4.2 µm^2 to 4.9 µm^2. As a result, the output saturation power improves from 6 dBm to 6.3 dBm. Similarly, we assessed the influence of the core layer thickness variation on the SOA performance (by fixing the core thickness at 120 nm and width at 2 µm). As Fig. 2(d) indicates, the PDG variation is between 2.4 dB and 3.6 dB. As for the thinner core layer of 100 nm and 110 nm the PDG is around 3.2 dB and 3.3 dB, respectively. On the other hand, for thicker core layers, i.e., 130 nm and 140 nm, the PDG decreases to 2.4 dB due to the improvement of confinement factor ratio (c.f. Fig. 2(c)). The output saturation power varies between 0.6 dB, as core layer thickness increases from 100 nm to 140 nm.

III. CONCLUSIONS

In conclusion, we designed and investigated PI SOA based on bulk active layer in C- and L- band suitable for active-passive monolithically co-integration. Results indicate low PDG (< 3.6 dB), high output saturation power (6.4 dBm), and high gain (19.8 dB) operation of the SOA. Finally, the results show that the fabrication tolerance of active layer thickness has not profound effect on the PDG and output saturation power variation. PDG and output saturation power vary by 1 dB, and 0.6 dB as the thickness of the active layer changes by ±10 % because of fabrication tolerance.

ACKNOWLEDGMENT

This work has been supported by the European ICT project QAMeleon funded under Horizon 2020.

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