Non-destructive gain measurement method for three cascaded SOAs on photonic integrated chips

Xudong Wang[1,2], Bin Shi[1], Lin Liu[2], Yutang Ye[2], Yong Liu [2] and Ripalta Stabile[1]

[1] Eindhoven Hendrik Casimir Institute, Eindhoven University of Technology, 5600 MB Eindhoven, The Netherlands

[2] Ministry of Education and State Key Laboratory of Electronic Thin Films and Integrated Devices, University of Electronic Science and Technology of China, Chengdu 610054, China

Abstract

We experimentally verify a bonding-less non-destructive gain measurement method for three cascaded SOAs on photonic integrated chips.

Introduction

SOAs have attracted a lot of interest because of their application potential in the fields of optical communications. Simultaneously, owing to advances in fabrication technology and device design, they are evolving as a promising candidate for future optical coherent communication links [1]. Photonic integrated devices based on SOA have been envisioned for all-optical signal processing tasks at very high bit rates that cannot be handled by electronics, such as wavelength conversion [2], optical switching [3], photonic neural network chips [4], aiming to increase computing speed and energy efficiency. Specifically, among them, indium phosphide (InP) SOA-based PICs offer the prospect of highly efficient optical communications networking [5].

Therefore, SOAs, especially cascaded SOAs, are widely used in PICs. However, for these PICs, how to quickly, efficiently, and non-destructively test whether the parameters and performance of SOAs, especially for the gain of cascaded SOAs, can meet the design requirements becomes an extremely important and urgent issue.

In this paper, we demonstrate a non-invasive pre-screening measurement method for three cascaded SOAs-based networks on chips, and experimentally verify the feasibility of the method on three cascaded SOAs-based PIC. This method is based on the analysis of both ASE noise and path losses from each stage SOA and of all photocurrents generated when injecting light into each stage SOA in both the forward and backward directions.

Experimental method and setup

A SOA can be regarded as an optical amplifier (OA) when a bias current is applied but can also be regarded as a photoelectric detection (PD) when no bias current is applied. The generated photocurrent I_{PD} is proportional to the incident light intensity, which includes both signal and noise contributions:

$$I_{PD} = I_s + I_{ASE} = \alpha P_{in} \tag{1}$$

where α is the photoelectric conversion factor and P_{in} is incident optical power. Because of the optical path reversibility, in a 3 SOAs path net, the losses encountered between the 3 SOAs, when light propagates in the forward ($L_{12}\ and\ L_{23}$) and backward ($L_{21}\ and\ L_{32}$) directions are identical ($L_{12} = L_{21} = L_1$; $L_{23} = L_{32} = L_2$). Based on the principle of photogenerated current, we can calculate the input optical power of the current SOA and the output optical power of the previous SOA, including path loss between the current and previous SOA. The same method is applied both in the forward- and backward propagation of the light (orange and green path in Fig. 1, respectively), so that the SOA gain as well as path loss can be calculated. We operate following 3 measurement settings:

Setting-I (For photoelectric conversion factor)**: SOA1 and SOA3 used as PDs.** When the input optical power to SOA1, is P_{Rin}, and we turn on the switch K_{A1}, the measured current is I_1^R : the measured right current of SOA1 displayed by the ammeter. Then, $\alpha_1 and\ \alpha_3$[A/W] can be calculated as:

$$I_1^R = \alpha_1\ P_{Rin} \tag{2}$$

$$I_1^L = \alpha_3\ P_{Lin} \tag{3}$$

In this experiment, considering the same manufacturing process and material, we take the photoelectric response factor for SOA2 as equation (4). Additionally, P_n^R indicates the ratio of the current measured when the SOA**n** acts as a PD in the right propagation direction to the photoelectric influence factor α_{n} of the SOAn ($I_n^R/\alpha_n = P_n^R, n = 1{,}2{,}3$).

$$\alpha_2 = (\alpha_1 + \alpha_3)/2 \tag{4}$$

Setting-II (For the Gains of forward (Right) propagation) **. SOA1 used as OA and SOA2 as PD.** We turn off K_{A1} and K_{c2}, and turn on K_{c1} and K_{A2} and tune C1 to make SOA1 works as OA under I_1 (0 mA - 90 mA). Simultaneously, the SOA2 works as PD with the A2 reading light propagating in the right direction, I_2^R (Fig. 1). Hence, we can use equation (4) to obtain the P_{Ro1}, the output power in forward propagation of SOA1 containing L_{12} under different driving currents I_1, the P_{Ri2} . With input power in forward propagation of SOA2, Gain G_1^R (unit in dB) of SOA1 in forward propagation is:

$$G_1^R = (P_2^R + L_1 - P_{in}) \tag{5}$$

Similarly, **SOA1**, **SOA2 used as OA and SOA3 as PD.** We turn off K_{A1}, K_{A2} and K_{c3}, and turn on $K_{c1}, K_{c2}$and K_{A3} and tune C1, C2 to make SOA1 and SOA2 works as OA under I_1 (0 mA - 90 mA) and I_2 (0 mA - 70 mA). Simultaneously, the SOA3 works as PD with the A3 reading light propagating in the right direction, I_3^R (Fig. 1). Hence, we can use equation (4) to obtain the P_{Ro2}, the output power in forward propagation of SOA2 containing L_{23} under different driving currents I_2, the P_{Ri3} , the input power in forward propagation of SOA3 and G_2 as Gain of SOA2 in forward propagation (G_2^R) is:

$$G_2^R = (P_3^R + L_2) - P_2^R \tag{6}$$

Furthermore, **SOA1**, **SOA2 and SOA3**, **used as OAs**. Adjust the optical attenuator to 0 to make Prin fixed. Adjust the corresponding switches and equipment make three SOAs work in their respective OA states ($I_1 = 90mA; I_2$ (0 mA - 70 mA) and I_3 (0 mA - 100 mA)). Connect the output signal of SOA3 to OSA to display and collect the waveform. The gain of SOA3 in forward propagation (G_3^R) is:

$$G_3^R = P_{ROut} - P_3^R \tag{7}$$

Setting-III (For the Gains of backward (Left) propagation) . As shown in Fig. 1, similar to the operation in forward propagation (Right), adjust the corresponding switches and let these three SOAs work in different states respectively. In this way, G_3^{L} $G_2^{\mathrm{L}} and\ G_1^{\mathrm{L}}$is obtained as follows:

$$G_3^L = (P_2^L + L_2)\ -\ P_{Lin} \tag{8}$$

$$G_2^L = (P_2^L + L_2) - P_2^R \tag{9}$$

$$G_1^L = P_{LOut} - P_1^L \tag{10}$$

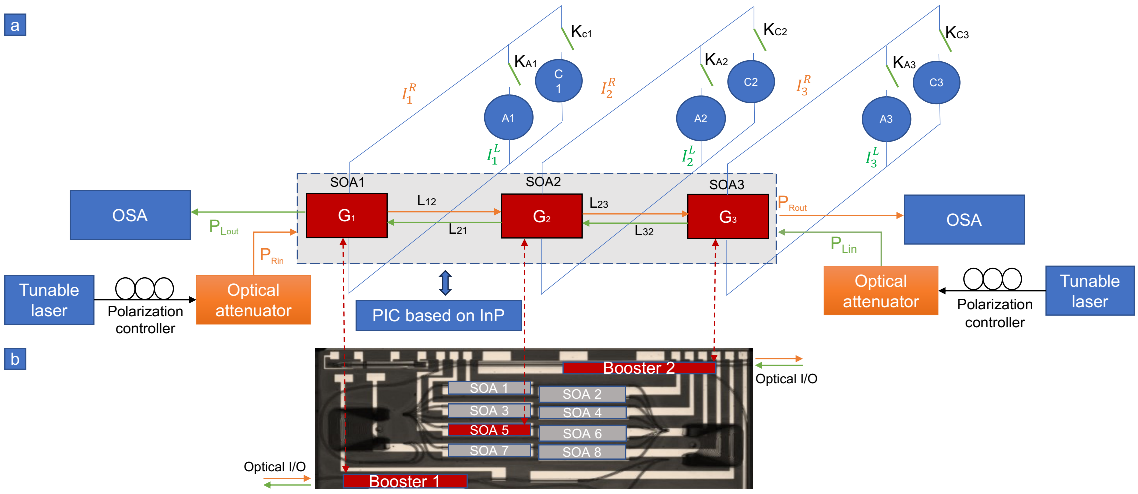

Fig. 1. Experimental setup for gain measurement for three cascaded SOA, with light propagated in dual directions. $\boldsymbol{K_{A1}}$, $\boldsymbol{K_{A2}}$ and $\boldsymbol{K_{A3}}$ are used to select whether to connect the ammeter to SOA_1, SOA_2 and SOA_3 respectively. $\boldsymbol{K_{C1}}$, $\boldsymbol{K_{C2}}$ and $\boldsymbol{K_{C3}}$ are used to select whether to connect to the current source for SOA_1, SOA_2 and SOA_3 respectively. Dotted box in (a) is a logical abstraction of part (b) of the PIC.

Experimental Results and Analysis

As shown in Fig. 1b, the micrography of SOA-based optical neural network chip with SOA schematics shows the fabricated integrated chip used in this work. Here are 3 SOAs in our test experiment, specifically Booster 42, SOA_5 and Booster 1 on this chip, which correspond to SOA_1, SOA_2 and SOA_3 respectively. According to testing, the coupling loss of the fiber to the facet of the waveguide is taken as 7dBm (for both SOA_1 and SOA_3) in the experiments.

Fig.2 (a-c) shows the comparison of the gain curves of SOA_1, SOA_2 and SOA_3 in two directions (blue represents the forward direction, and orange represents the backward direction). Combined with the above three reasons and Fig. 2(a-c), each gain curve of cascaded SOA in different directions can be regarded as the result that the real SOA gain curve is affected or modulated by the main ASE noise and path loss in a specific direction. Furthermore, Equation (11-16) can be used to illustrate to some extent how the gain of each SOA in a particular direction is affected by the corresponding noise and path loss.

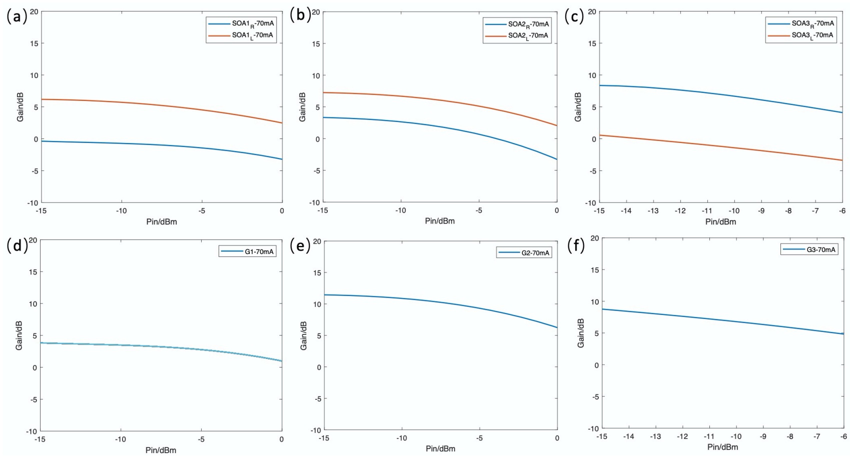

Fig. 2. Experimental results for three cascaded SOAs. (a) Comparison plots of between $\boldsymbol{G_1^R}$ and $\boldsymbol{G_1^L}$ curves from SOA1 for $\boldsymbol{I_{b1}}$= 70 mA, (b) plots of $\boldsymbol{G_2^R}$ and $\boldsymbol{G_2^L}$curves from SOA2 for $\boldsymbol{I_{b2}}$= 70 mA, (c) plots of $\boldsymbol{G_3^R}$ and $\boldsymbol{G_3^L}$curves from SOA3 for $\boldsymbol{I_{b3}}$= 70 mA; The gain curves of G_1 (d), G_2 (e) and G_3 (f) from SOA_1, SOA_2 and SOA_3 calculated by the method.

$$G_1^1 = P_s + N_1 - L_1 - P_{rin} = G_1 + N_1 - L_1 \quad (11)$$
$$G_1^2 = P_{Lout} - (P_{Lin1} + N_2) = G_1 - N_2 \quad (12)$$
$$G_2^1 = P_s + N_2 - L_2 - P_{rin2} = G_2 + N_2 - L_2 \quad (13)$$
$$G_2^2 = P_s + N_2 - L_1 - P_{Lin2} = G_2 + N_2 - L_1 \quad (14)$$
$$G_3^1 = P_{Rout} - (P_{Rin3} + N_2) = G_3 - N_2 \quad (15)$$
$$G_3^2 = P_s + N_3 - L_2 - P_{Lin} = G_3 + N_3 - L_2 \quad (16)$$

Additionally, when the noise and path loss are removed, the real gain of each SOA under its specific current can be obtained by combining the formula (11-16). Fig. 2(d-f) shows the obtained gain curves of three SOAs.

For three cascaded SOAs, based on the above experimental methods and setup we obtain the gain curves of SOA_1. However, a significant difference is found between the differently calculated $G_1^{\mathrm{R}}$and G_1^{L} curves for SOA_1 at the same current. This could be due to various reasons:

(1) Both the noise from ASE of each SOA and the path losses (L_1 and L_2) as the most dominant factors, cause differences in the gain measurement in different directions, which are evident in the low-optical power regime.

(2) The gain G_1^{L} is meaningful only in the larger power regime, as in the backward direction, the input power of SOA_1 is obtained by changing the bias current of SOA_2. Only when the bias current of SOA_2 is greater than a certain threshold, the optical signal can pass through or be amplified.

(3) The integration property of the PD is unable to effectively distinguish between signal current I_s and I_{ASE} when the SOA is used as PD, as seen in Equation (1).

Conclusions

We demonstrate a non-invasive gain measurement method for cascaded SOA-based PICs based on the combination of the use of SOAs as PDs and OAs and on the accesses to only the first and last SOA stages in the chain and in both directions; After removing the ASE and path loss effect of the SOA gain curves, the real gain and the path losses in cascaded SOA paths can be obtained.

This non-invasive, pre-screening characterization solution for the three cascaded SOA performance testing, paves the way for automated testing of more than 3 cascaded SOAs and makes it possible to exploit as a method for cascaded SOA-based PIC wafers.

References

[1] Aneesh Sobhanan, Aravind Anthur, Sean O'Duill, Mark Pelusi, Shu Namiki, Liam Barry, Deepa Venkitesh, and Govind P Agrawal, "Semiconductor optical amplifiers: recent advances and applications," Adv. Opt. Photon. 14, 571-651 (2022).

[2] Yu Wang and Nicola Calabretta, "Polarization-insensitive 40-channel 100-GHz spacing fold-back planar echelle grating Mux/Demux for photonic integrated wavelength-selective switches," Opt. Lett. 47, 5268-5271 (2022). DOI:org/10.1364/OL.470802.

[3] Stabile R, Rohit A, Williams KA. "Monolithically integrated 8×8 space and wavelength selective cross-connect". Journal of Lightwave Technology 2013; 32: 201–207.

[4] Bin Shi, Calabretta, N., & Stabile, R. (2022). "SOA-based All-optical Photonic Integrated Deep Neural Network with Stable Output Noise". In European Conference on Optical Communication (ECOC) 2022

[5] Stabile, R., Albores-Mejia, A., Rohit, A. et al. Integrated optical switch matrices for packet data networks. Microsyst Nanoeng 2, 15042 (2016)