Comparison of multisectional SOAs for gain and absorption measurement

D. I. Pustakhod, M. K. Smit, and X. J. M. Leijtens

Eindhoven University of Technology, Dept. of Electrical Engineering
Den Dolech 2, 5600 MB, Eindhoven, The Netherlands

Semiconductor optical amplifiers (SOA) are widely used in chips manufactured on InP active-passive integration technologies. Their key characteristics, gain and absorption spectra, are important for designing active circuits and also act as an indication of the overall quality of the fabrication. We investigate multisectional SOAs as test structures which allow quick and reliable measurement of both these parameters. The measurement results from a COBRA MPW run are presented. We compare the accuracy of the measurement using multisectional SOAs of different geometry.

Introduction

InP-based generic integration technology is increasingly used in the last years [1]. This approach provides the possibility to design complex circuits using standard qualified library building blocks (BB), such as waveguides, arrayed waveguide gratings (AWG), semiconductor optical amplifiers (SOAs), and detectors. With this design methodology no detailed knowledge about the manufacturing process is required from the designer. Designs from of different users may be combined in so-called multi-project wafer runs (MPW) and the costs of prototyping are shared among all the users participating in it.
The control and verification of the fabrication process is the responsibility of the foundry, which employs test cells for this purpose. These cells may contain pass/fail test structures, which only indicate if the performance of the BBs is within specification or not. However, more powerful test structures will allow one to measure this performance and supply designers with the data required for accurate circuit simulations. The main requirements to the test circuits and measurement methods are simplicity, speed and footprint on the cell. There is progress in development of fully electrical testing methods [2], making use of integrated light sources and detectors. They reduce the testing to measuring electrical performance of test circuits and deriving optical characteristics from the values obtained. In the present article we study test structures that require coupling light out of test circuits and subsequently analyse it with external equipment. This latter method benefits from the functionality present in external tools which is at the moment not available in integrated circuits, e.g. to measure the optical spectrum.
In the present work we concentrate on the development of test structures with optical outputs meant for measuring gain and absorption spectra of SOAs, which are of particular importance for building on-chip lasers, amplifiers and detectors.

Methods of gain measurement

There is one group of methods which uses the amplified spontaneous emission (ASE) spectrum of a Fabry–Pérot (FP) laser [3, 4, 5]. They achieve accurate measurements of the gain with $\Delta G \simeq 0.1\text{cm}^{-1}$. However, the highest accuracy is achieved at current densities just below the threshold current for a particular FP laser, and for the densities above threshold these methods cannot be used at all.

Another group of methods is based on the measurement of the ASE spectrum as a function of the SOA length, as proposed by Oster [6]. It makes use of the relation between output intensity P_{out} and the SOA length L

$$P_{\text{out}}(\lambda, L) = \frac{P_{\text{sp}}(\lambda)}{G(\lambda)}(e^{G(\lambda)L} - 1), \tag{1}$$

where P_{sp} is the intensity of the spontaneous emission per unit length, and G is net modal gain. Once we have a set of spectra $P_{\text{out}}^{(i)}$ for a set of SOA of $L^{(i)}$ in length, we can obtain $G(\lambda)$ and $P_{\text{sp}}(\lambda)$. This can done by direct calculation using Thomson's approach [7], in which two ASE spectra from SOAs of length L and $2L$ are used:

$$G(\lambda) = \frac{1}{L}[\ln(\frac{P(\lambda, L)}{P(\lambda, 2L)} - 1)], \tag{2}$$

Another way to extract the gain is to use fitting to (1) of measurements with different values of P_{out} and L. This method has an intrinsic indication of the fitting quality, namely the residual sum of squares. It can be used to discard poor measurement results, e.g. due to a broken test structure.

Multisectional SOAs for ASE measurements

Two factors play crucial role in the applicability of the second group of methods. First, the same light collection efficiency for all measured structures should be achieved. This includes coupling loss and waveguide loss. The Thomson formula (2) is very sensitive to this factor. For example, 0.2 dB variation in the measured ASE power from a 100 µm SOA for a gain $G \sim 40\,\text{cm}^{-1}$ leads to an error in the gain of $\Delta G \sim 7\,\text{cm}^{-1}$. To increase coupling stability a multisectional SOA (MS-SOA) was proposed [7].
Second, the measured P_{out} should be single-pass amplified intensity, which means that light should go through the SOA only once. Any reflections from the facet or from the active-passive interface make (1) no longer valid.

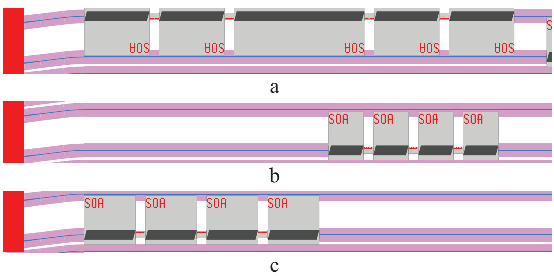


Figure 1: Mask layout of MS-SOAs. Lengths of sections: (a) $L_{\text{SOA}} = 200, 200, 400, 200, 200$ µm. (b) $L_{\text{SOA}} = 100$ µm. (c) $L_{\text{SOA}} = 150$ µm.

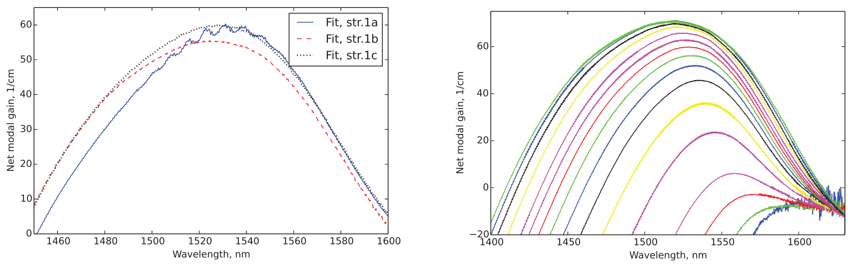
Design of test structures

We designed and manufactured test structures (fig. 1) on a Smart Photonics MPW run. The whole structure is built on a shallow waveguide [1]. MS-SOA consists of an angled waveguide output on the chip facet, which is connected to the SOA building blocks of different length. Between each SOA is a 30 μm section that provides electrical isolation. In order to prevent reflections from the facet, angled output waveguides at a 7° angle were used and the facet was provided with an antireflection coating. The active-passive butt-joints are angled for the same purpose.

By biasing only the first SOA, then the first two, etc. one can measure the output intensity from SOAs of various lengths. The SOA lengths of the test structure of fig. 1a were selected to give a total length of SOA of $L_{\text{total}} = 200, 400, 800, 1000\,\text{um}$. This allows us to use the Thomson formula for a pair 200-400 μm, 400-800 μm, and to use the fitting method for all four lengths. The length distribution of the other two structures, fig. 1b,c was chosen specifically for fitting method with equal sections of 100 and 150 μm in length respectively.

Gain measurement

We calculated the gain using both the Thomson method and the fitting method for all three test structures for current densities in the range of $J = 0.25..9\,\text{kA/cm}^2$. In general, fitting reduces the noise on the gain curve compared to the Thomson formula. The comparison of the measured gain obtained from fitting of three different structures is shown in fig. 2a. Even though we use angled facets and antireflection coating, FP fringes on the ASE spectrum start being visible already at current density of $J = 4\,\text{kA/cm}^2$ for the test structure of fig. 1a. This leads to a significant ripple on the gain in the the region with maximum gain and a reduction of the gain at smaller wavelengths. Instead, for the shortest structure (fig. 1a) the ASE intensity is not high enough, and absorption in the waveguides has a higher impact which also results in incorrect gain values.



a b

Figure 2: Calculated net modal gain. (a) Comparison of gain calculated with three structures. (b) Gain for different pump currents measured on the structure of fig. 1c.

The calculated gain spectra at current densities in the range $J = 0.25..9\,\text{kA/cm}^2$ are shown in fig. 2b.

Absorption measurement

Absorption properties can be studied by reverse biasing the SOA which is the closest to the output. In this case it acts as an absorber for the light emitted by the other SOA sections. In order to calculate the absorption we assume it complies to the Beer–Lambert law [8]

$$P_{\text{out}}(\lambda) = P_{\text{in}}(\lambda) e^{-\alpha(\lambda, V_{\text{RB}}) L_{\text{SOA}}}, \tag{3}$$

where $\alpha(\lambda, V_{RB})$ is the absorption coefficient which is dependent on the applied reverse voltage V_{RB}, and L_{SOA} is the length of the reversely biased SOA. P_{in} can be calculated based on the values obtained for G and I_{sp}, or which can be measured directly for test structures in fig. 1 in case of structures fig. 1b,c can be measured directly.

The result of calculations for different incoming power levels $P_{in}(\lambda)$ is shown in fig. 3. The difference in the calculated values can be explained by the the noise floor P_{noise} which has to be added to the right side of (3). Options for excluding P_{noise} in the calculations are being investigated.

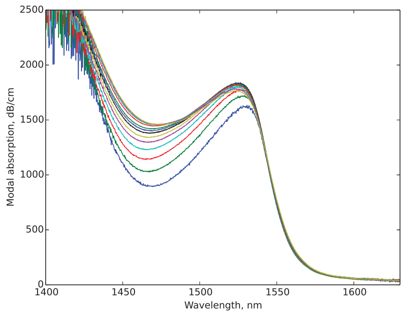


Figure 3: Calculated SOA absorption spectra. Different curves correspond to different levels of P_{in}

Conclusions

We discussed three test structures for measuring the gain and absorption of SOAs. Experimental results for the Smart Photonics platform show that multisectional SOAs can be successfully used for these measurements. The fitting method results in a less noisy gain curve for all measured structures, and has the additional benefit that it gives information about the quality of the fit, which the Thomson method does not. The structure of fig. 1c in combination with the fitting method was found to be optimum for gain measurements on the selected platform. Using the same structure, first measurements of the absorption coefficient have been carried out, but accurate extraction of the absorption coefficient requires further study.

Acknowledgement

This research is carried out in the ProCon Project 11369, supported by the Dutch Technology Foundation STW, which is part of the Netherlands Organization for Scientific Research (NWO), and which is partly funded by the Dutch Ministry of Economic Affairs.

References

[1] M. K. Smit, X. Leijtens, H. Ambrosius, *et al.*, "An introduction to InP-based generic integration technology," *Semicond. Sci. Technol.*, vol. 29, p. 083001, 2014.

[2] E. Bitincka, R. G. Broeke, and M. K. Smit, "Progress report on on-wafer testing of Photonic Integrated Circuits (PICs)," in *Proceedings of the 18th Annual Symposium of the IEEE Photonics Society Benelux Chapter, 25–26 November 2013, Eindhoven, The Netherlands*, pp. 61–64, 2013.

[3] B. W. Hakki and T. L. Paoli, "Gain spectra in GaAs double-heterostructure injection lasers," *J. Appl. Phys.*, vol. 56, no. 3, pp. 1299–1305, 1975.

[4] H. Wang and D. T. Cassidy, "Gain measurements of Fabry–Pérot semiconductor laser using a nonlinear least-squares fitting method," *IEEE J. Quantum Electron.*, vol. 41, pp. 532–540, 2005.

[5] M. Zhang, D. Liu, and T. Makino, "Measurement of gain spectra of semiconductor lasers using least squares fitting method," *IEEE Photonics Technology Letters*, vol. 25, pp. 1122–1124, June 15 2013.

[6] A. Oster, G. Erbert, and H. Wenzel, "Gain spectra measurements by a variable stripe length method with current injection," *Electronics Letters*, vol. 3, pp. 864–866, 5 1997.

[7] J. D. Thomson, H. D. Summers, P. J. Hulyer, P. M. Smowton, and P. Blood, "Determination of single-pass optical gain and internal loss using a multisection device," *Appl. Phys. J.*, vol. 75, no. 17, pp. 2527–2529, 1999.

[8] S. A. Akhmanov and S. Y. Nikitin, *Physical Optics*. Oxford University Press, June 12 1997.