Flat Noise Figure Semiconductor Optical Amplifiers

Shuqi Yu, Antonin Gallet, Nayla El Dahdah, Hajar Elfaiki, Iosif Demirtzioglou, Loig Godard, Romain Brenot
Optical Communication Technology Lab, Paris Research Center, Huawei Technologies, 20 quai du Point du Jour 92100 Boulogne Billancourt France, shuqi.yu@huawei.com

Abstract We propose a new SOA design with a detuned material at the input in order to guarantee low noise figure (NF) over the whole gain spectrum. NF reduction of 1.5 dB is experimentally achieved, and NF remains below 6.5 dB over C and L bands.

Introduction

The Noise Figure (NF) of Semiconductor Optical Amplifiers (SOA) is usually considered too large for some applications, such as in-line amplification or pre-amplification. Compared to Fibre Amplifiers, SOA present coupling losses, significant propagation losses and incomplete carrier inversion. By carefully designing the SOA, some groups have demonstrated a NF below 6 dB [1],[2]. However, the NF is wavelength dependent and increases at the blue side of the gain spectrum in respect to the gain peak position, limiting the optical bandwidth of the SOA if an upper limit for NF has to be considered. This might be slightly mitigated with a multi-electrode design [3], but Auger effect and thermal impairments will limit the reduction of NF at high energies. In this paper, the root cause of the NF increase at shorter wavelengths than the gain spectrum peak position is investigated. Based on the NF analysis results, a new design exhibiting less than 1dB NF variation across the Gain spectrum will be presented. We propose to insert a carefully designed input section with a detuned gain peak compared to the main part of the SOA, which will very efficiently improve carrier inversion at the SOA input, where most of NF increase takes place. We will describe a practical implementation scheme and experimentally validate our approach.

Definition and analysis of SOA NF

The NF is a quantified measurement of the electrical Signal-to-Noise Ratio degradation encountered by an optical signal amplified by a SOA[4].
The SOA NF can be expressed as follows[5]:

$$\mathrm{NF}(\lambda) = \frac{2}{\mathrm{C}} \frac{\Gamma\,\mathrm{g}}{\Gamma\,\mathrm{g}-\alpha} \frac{1}{1-\exp\left(\frac{\mathrm{hc}/\lambda-\Delta\mathrm{E_F}}{\mathrm{kT}}\right)} \qquad (1)$$

where C is the coupling efficiency, Γ the optical confinement in the active layer, g the material gain and α the total propagation losses. These terms depend on wavelength. ΔE_F is the separation between quasi-Fermi levels. It corresponds to the energy where absorption and stimulated emission have the same probability. It is also called the transparency energy, although the gain is slightly negative in dB at this energy due to the propagation losses. When expressed in dB, the NF is the sum of four terms:

$$NF(\lambda) = 3 + \mathrm{CL} + 10\log\left(\frac{\Gamma\,\mathrm{g}}{\Gamma\,\mathrm{g}-\alpha}\right) - 10\log\left(1 - \exp\left(\frac{\mathrm{hc}/\lambda-\Delta\mathrm{E_F}}{\mathrm{kT}}\right)\right) \qquad (2)$$

CL=-10log(C) is the input coupling loss in dB.
The third term is called the loss term. It increases the NF if low optical confinement is targeted, unless propagation losses are minimized. This is usually done by inserting a thick under-cladding layer below the active layer[1],[6], in the n-doped part of the SOA stack. The refractive index of this cladding layer has to be slightly larger than the one of InP, in order to attract the optical mode in the n-doped layers, away from lossy p-doped layers.
The last term of equation (2) is the carrier inversion term.

Standard SOA using a thick under-cladding layer were made using InGaAsP multi-quantum wells for the active region. The active stripe was tilted by 7deg with respect to the cristallographic direction to reduce optical feedback. Anti-reflection coating was also applied to the optical facet in order to achieve less than 10^{-6} effective facet reflectivity. The fibre-to-fibre gain and the coupling loss were measured in the linear regime as a function of the wavelength for a L=4mm long SOA (Fig 1).

978-1-6654-3868-1/21/$31.00 ©2021 IEEE

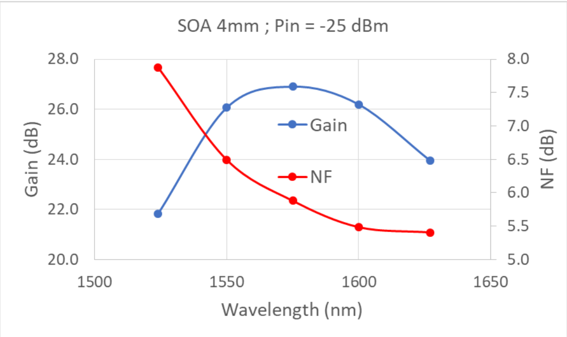

Fig. 1: Measured gain and NF of a 4 mm long SOA

The NF increases significantly at the blue side of the gain spectrum in respect to gain peak position. For instance, if our SOA had to operate with NF below 6 dB, only half of the gain spectrum could be used, whereas NF reaches 5.5dB on the red part of its gain spectrum. In order to understand its root cause, the different terms of equation (2) were calculated and the resulting NF (simulated NF) was compared to the measured NF (Fig 2).

By using a standard mode solver, the optical confinement in MQW and cladding layers was calculated, from which the optical confinement Γ and the propagation losses are deduced as a function of the wavelength. Since the measured gain G_{lin} can be expressed as follows:

$$G_{\text{lin}}(\lambda) = C^2 \exp\big((\Gamma g - \alpha)\, L\big) \qquad (3)$$

Or, G in dB:

$$G(\lambda) = \frac{10}{\ln(10)}(\Gamma g - \alpha)\, L - 2\, CL \qquad (4)$$

The material gain $g(\lambda)$ was extracted for a given current density. It should be noted that these calculations are only valid in the case the Spatial Hole Burning is negligible, which is usually the case for low confinement SOA[7].

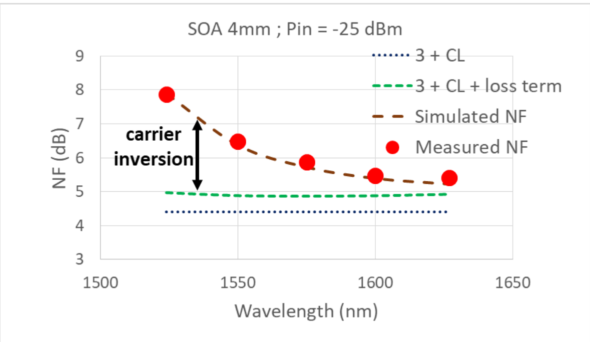

Fig. 2: Calculated and measured NF of a 4 mm long SOA

Good agreement was found between the measured and simulated NF validating the analytical expression of the SOA NF. In Fig 2, the coupling loss (3+CL) and total loss (3+CL+loss term) were also plotted and compared to the NF. Since the formers don't vary significantly with wavelength, the increase of the NF at short wavelength is mainly due to the partial carrier inversion at the corresponding energy levels. The only fitting parameter is the transparency wavelength, 1.49 um (i.e. ΔE_F = 1.24/1.49 = 0.83 eV). This wavelength corresponds to the absorption edge visible on the short wavelength part of the Amplified Spontaneous Absorption (ASE) spectrum.

Proposed design to reduce NF

The carrier inversion term could be reduced by increasing the carrier density at the input of the SOA, but the improvements will be limited by Auger effect which limits the increase of the carrier density with increased current density. The most straightforward way to reduce this term is to increase ΔE_F. This might be done by increasing the gap energy of the active material, but this would shift the gain peak and lead to a significant gain decrease at the red side of the spectrum. Here, we investigate the implementation of a higher gap material only at the input of the SOA by resorting to the well-known Butt-Joint (BJ) technique. This technique is commonly used to fabricate Electro-Absorption Modulated Lasers.

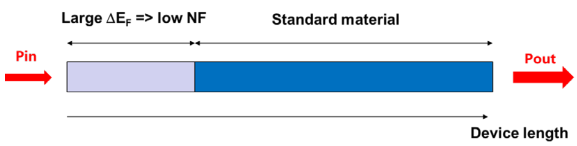

Fig. 3: Top-view of proposed low NF SOA design

The length of the input section should be sufficiently long to reduce the impact of the main section on the NF, and sufficiently short to reduce the shift of the gain peak. The BJ is carefully designed to avoid any unwanted reflection at the interface between both materials.

Experimental validation

SOA devices were made with different length (0, 1, 2 and 4mm) of BJ section. The BJ section design is almost similar to the standard (STD) material, except the Photo-Luminescence peak is 30 nm blue-shifted. The SOA without a BJ section is referred to by STD.

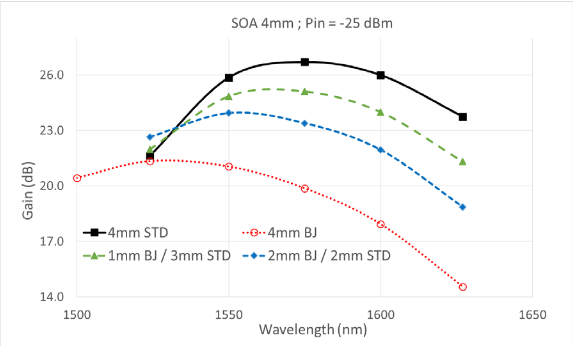

Fig. 4: Measured gain of 4 mm long SOA, made with 0, 1, 2 or 4 mm of BJ material.

Fig. 4 shows the gain measured on the 4 SOA designs. The 4mm BJ SOA has a blue-shifted gain spectrum, but the gain values are 5-6 dB lower than the ones of STD SOA. This might be due to the regrowth on the thick under-cladding. The SOA with only 1mm of BJ has similar gain peak position as STD SOA, whereas, as expected, the 2mm BJ SOA presents 25nm blue-shift of the gain peak.
Fig. 5 shows the measured NF of these four SOA.

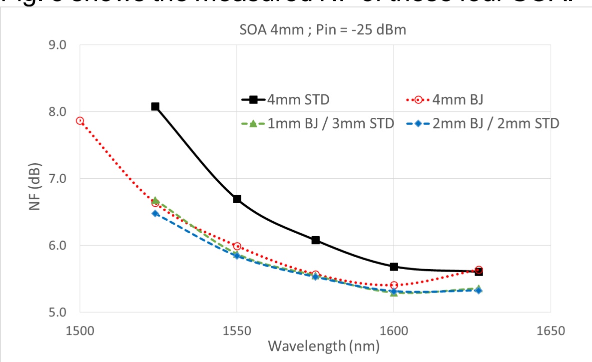

Fig. 5: Measured NF of 4 mm long SOA, made with 0, 1, 2 or 4 mm of BJ material, and the rest with standard material.

The NF spectrum of 4mm BJ SOA is blue shifted compared to STD SOA, and starts to increase beyond 1600 nm due to an insufficient gain, which increases the loss term. NF spectrum of 1mm and 2mm BJ SOA was measured identical to the NF spectrum of 4mm BJ SOA except at long wavelength since the gain is sufficient in these cases. In particular, the device with only 1mm of BJ material allows to extend the useful optical bandwidth of SOA, by allowing to operate across the gain spectrum with NF <6.5 dB. Furthermore, the NF is reduced across the gain spectrum on both sides of the gain peak position in respect to the standard device.
If the BJ section is put at the output of the SOA, then NF spectrum is measured similar to the standard SOA's. This validates the new SOA design with BJ material at the input section to address the NF variation issue across the Gain spectrum.

Conclusions

The various contributions in the SOA NF were carefully analysed in order to understand the NF variation across the gain spectrum. Based on measurements and calculations, the carrier inversion was found responsible for NF increase when wavelength decreases below the gain peak spectral position. With the insertion of a detuned material on one fourth to half of the SOA length, at its input, the NF increase was reduced by 1.5dB. Further optimizations of this input section might lead to even lower NF values. A dedicated electrode might be useful, since carrier density is probably smaller at the input in this case because of a larger material gap. Selective Area Growth or a second BJ might also be beneficial to fine-tune carrier inversion profile at the SOA input.

Acknowledgements

The authors wish to thank Almae Technologies for the fabrication of the devices.

References

[1] P. W. Juodawlkis et al, "Packaged 1.5-um Quantum-Well SOA With 0.8-W Output Power and 5.5-dB Noise Figure", *IEEE Photon. Technol. Lett.*, vol. 21, no. 17, pp. 1208–1210, Sept. 2009

[2] K. Morito, S. Tanaka, S. Tomabechi, and A. Kuramata, "A broad-band MQW semiconductor optical amplifier with high saturation output power and low noise figure," *IEEE Photon. Technol. Lett.*, vol. 17, no 5, pp. 974–976, May 2005.

[3] R. Lennox et al, "Impact of bias current distribution on the noise figure and saturation power of a multicontact semiconductor optical amplifier", Optics Letters, vol. 36, no. 13, pp. 2521-2523, July 2011.

[4] D. M. Baney, P. Gallion, and R. S. Tucker, "Theory and measurement techniques for the noise figure of optical amplifiers," *Opt. Fiber Technol.*, vol. 6 (2000), pp. 122–154

[5] K.S. Jepsen et al, "Wavelength Dependence of Noise Figure in InGaAs /InGaAsP Multiple-Quantum-Well Laser Amplifier", IEEE Photonics Technol. Lett. Vol. 4 (1992), pp. 550–553.

[6] A. Verdier *et al*, "Ultrawideband wavelength-tunable hybrid external-cavity lasers," *Journal of Lightwave Technology*, vol. 36, no. 1, pp. 37–43, 2018.

[7] F. Pommereau et al, "Realisation of Semiconductor Optical Amplifiers with Homogeneous Carrier Density and Low Noise Factor", in Proc. Int. Conf. Indium Phosphide Relat. Mater., May 2005, pp. 102–105