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TECHNICAL REPORT

Optical amplifiers –
Part 9: Semiconductor optical amplifiers (SOAs)

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colour inside

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OPTICAL AMPLIFIERS –

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FOREWORD

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This redline version of the official IEC Standard allows the user to identify the changes made to the previous edition IEC TR 61292-9:2017. A vertical bar appears in the margin wherever a change has been made. Additions are in green text, deletions are in strikethrough red text.

IEC TR 61292-9 has been prepared by subcommittee 86C: Fibre optic systems and active devices, of IEC technical committee 86: Fibre optics. It is a Technical Report.

This third edition cancels and replaces the second edition published in 2017. This edition constitutes a technical revision.

This edition includes the following significant technical changes with respect to the previous edition:

a) revised definitions for SOAs in 3.1;
b) added more theoretical background on gain ripple measurements using amplified spontaneous emission (ASE) spectrum in 4.3;
c) removed the formerly preferred set-up for output power and PDG measurements in Clause 5.

The text of this Technical Report is based on the following documents:

Draft	Report on voting
86C/1820/DTR	86C/1830/RVDTR

Full information on the voting for its approval can be found in the report on voting indicated in the above table.

The language used for the development of this Technical Report is English.

This document was drafted in accordance with ISO/IEC Directives, Part 2, and developed in accordance with ISO/IEC Directives, Part 1 and ISO/IEC Directives, IEC Supplement, available at www.iec.ch/members_experts/refdocs. The main document types developed by IEC are described in greater detail at www.iec.ch/publications.

A list of all parts in the IEC 61292 series, published under the general title *Optical amplifiers*, can be found on the IEC website.

The committee has decided that the contents of this document will remain unchanged until the stability date indicated on the IEC website under webstore.iec.ch in the data related to the specific document. At this date, the document will be

- reconfirmed,
- withdrawn,
- replaced by a revised edition, or
- amended.

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INTRODUCTION

~~Optical amplifiers (OAs) are necessary components as booster, line and pre-amplifiers for current optical network systems. IEC TC 86/SC 86C has published many standards for OAs, and most of them are focused on optical fibre amplifiers (OFAs), which are commonly deployed in commercial optical network systems. Recently, semiconductor optical amplifiers (SOAs) have attracted attention for applications in gigabit passive optical network (GPON) and 100 Gbit Ethernet (GbE) systems. This is because SOA chips are as small as laser diodes (LDs) and only require an electrical current.~~

~~Although SOAs for the 1 310 nm or 1 550 nm bands have been extensively studied since the 1980s, the use of SOAs is still limited to laboratories or field trials. This is due to specific performance features of SOAs such as gain ripple and polarization dependent gain (PDG). Thus, there are very few IEC standards addressing SOAs. One example is IEC TR 61292-3, which is a Technical Report for classification, characteristics and applications of OAs including SOAs. However, it only deals with general information on SOAs and does not contain the detail information on test methods that are necessary to measure precisely the particular parameters of SOAs.~~

~~This part of IEC 61292 provides a better understanding of specific features of SOAs as well as information on measuring gain and PDG. It is anticipated that future standards will address performance and test methodology.~~

Optical amplifiers (OAs) are essential components for fibre optic communication systems, where they serve as booster amplifiers, in-line amplifiers, and pre-amplifiers. Numerous standards have been published for OAs (e.g., the IEC 61290 series and IEC 61291 series). However, most of these standards focus on optical fibre amplifiers (OFAs) because these are commonly deployed in commercial fibre optic networks. Recently, semiconductor optical amplifiers (SOAs) have attracted attention for applications in Gbit passive optical networks (GPONs) and Gbit Ethernet (GbE) systems, which operate at line rates of 100 Gbit/s and beyond. SOA chips are as small as laser diodes (LDs) and are directly driven by an electrical current.

Although SOAs operating in the 1 310 nm or 1 550 nm wavelength bands have been extensively studied since the 1980s, SOAs have mostly been used in laboratories or in field trials. This is due to certain performance limitations of SOAs, such as gain ripple and polarization dependent gain (PDG). As a result, there are few IEC documents addressing SOAs. One exception is IEC TR 61292-3, which is a Technical Report on classification, characteristics, and applications of OAs including SOAs. However, IEC TR 61292-3 presents only general information on SOAs and does not contain detailed information on test methods for measuring the particular performance parameters of SOAs.

IEC 61290-1-1:2020 describes test methods for power and gain parameters of OAs, which includes a method for gain ripple measurements on SOAs. This document has been revised to harmonize its content with IEC 61290-1-1 and with IEC 61291-2.

This document provides more detailed descriptions of the specific features of SOAs, including information on gain ripple and PDG.

OPTICAL AMPLIFIERS –

Part 9: Semiconductor optical amplifiers (SOAs)

1 Scope

This part of IEC 61292, which is a Technical Report, focuses on semiconductor optical amplifiers (SOAs), especially the specific features and measurement of gain and polarization dependent gain (PDG) describes the characteristic features of semiconductor optical amplifiers (SOAs), including the specific features of gain ripple and polarization dependent gain (PDG).

This document focuses on amplifying applications of SOAs. Other applications, such as modulation, switching and non-linear functions, are not covered.

Potential applications of SOAs, such as reflective SOAs (RSOAs) for the seeded wavelength division multiplexing passive optical network (WDM-PON), are reviewed in Annex A.

2 Normative references

There are no normative references in this document.

The following documents are referred to in the text in such a way that some or all of their content constitutes requirements of this document. For dated references, only the edition cited applies. For undated references, the latest edition of the referenced document (including any amendments) applies.

IEC 61291-1:2018, *Optical amplifiers – Part 1: Generic specification*

IEC 61291-2:2016, *Optical amplifiers – Part 2: Single channel applications – Performance specification template*

3 Terms, definitions, abbreviated terms and symbols

3.1 Terms and definitions

For the purposes of this document, the terms and definitions given in IEC 61291-1:2018, IEC 61291-2:2016, and the following apply.

ISO and IEC maintain terminological databases for use in standardization at the following addresses:

- IEC Electropedia: available at http://www.electropedia.org/
- ISO Online browsing platform: available at http://www.iso.org/obp

3.1.1
SOA
semiconductor optical amplifier
semiconductor optical amplifier that includes the "SOA chip" and the "SOA module"

optical amplifier in which the active optical waveguide is formed by a semiconductor laser diode structure, which is electrically pumped

Note 1 to entry: SOAs have a similar structure to Fabry-Perot semiconductor laser diodes but with anti-reflection elements at the end surfaces. The optical signal is amplified through the stimulated emission phenomenon in the gain medium.

[SOURCE: IEC 61291-2:2016, 3.1.3, modified – Note 1 to entry has been added.]

3.1.2
SOA chip
semiconductor chip that is the active component of the SOA module

3.1.3
SOA module
fibre-pigtailed optical component that consists of the SOA chip, lenses, optical isolators (if necessary), a thermoelectric cooler (TEC), a thermistor, a package, and optical fibre(s)

3.1.4
population inversion factor
n_{sp}
ratio of the injected carrier density N to the subtraction of the carrier density N_0 where the stimulated emission is equal to the stimulated absorption from N

$$n_{sp} = \frac{N}{N - N_0}$$

Note 1 to entry: In the semiconductor optical amplifier (SOA) field, the population inversion factor is composed of not only carrier density parameters but also combination of the confinement factor Γ, the optical gain g, and internal optical losses α of the optical waveguide of SOA chip. It is defined as:

$$n_{sp} = \frac{N}{N - N_0} \times \frac{\Gamma \times g}{\Gamma \times g - \alpha}$$

Note 2 to entry: The carrier density N_0 at which the stimulated emission is equal to the stimulated absorption ~~may be~~ is often called "transparent carrier density".

3.2 Abbreviated terms

AR	anti-reflection
ASE	amplified spontaneous emission
BPF	band pass filter
CFP	100 G form factor pluggable
CW	continuous wave
DEMUX	demultiplexer
DFB	distributed feedback
EDFA	erbium-doped fibre amplifier
FWM	four-wave mixing
GbE	gigabit Ethernet
GPON	gigabit capable passive optical network
LD	laser diode
MSA	multi-source agreement
MMI	multi-mode interference
MQWs	multiple quantum wells
NF	noise figure
OA	optical amplifier

OFA	optical fibre amplifier
OLT	optical line termination
ONU	optical network unit
~~OPM~~	~~optical power meter~~
PC	polarization controller
PD	photodiode
PDCE	polarization dependence of coupling efficiency
PDG	polarization dependent gain
PIC	photonic integrated circuit
POL	polarizer
PON	passive optical network
RSOA	reflective semiconductor optical amplifier
~~SLD~~	~~superluminescent diode~~
SMF	single-mode fibre
SOA	semiconductor optical amplifier
TE	transverse electric
TEC	thermoelectric cooler
TIA	transimpedance amplifier
TM	transverse magnetic
VOA	variable optical attenuator
WDM	wavelength division multiplexing
XGM	cross gain modulation
XPM	cross phase modulation

3.3 Symbols

G	optical gain
I_F	forward current
L	chip length
n_{eff}	effective refractive index
~~NF~~	~~noise figure~~
n_{sp}	population inversion factor
~~$PDCE$~~	~~polarization dependence of coupling efficiency~~
PDG_{active}	polarization dependence of active layer gain
PDG_{total}	total polarization dependence of single pass gain
R	reflectivity
ΔG_{ripple}	peak to peak amplitude of gain ripple
$\Delta\lambda_{ripple}$	period of gain ripple
Γ_{TE}	TE mode confinement factor
Γ_{TM}	TM mode confinement factor
λ	wavelength

4 Specific features of SOAs

4.1 SOA chips

Figure 1 shows the schematic diagram of a typical SOA chip. Similar to LDs, SOA chips are less than 1,5 mm in length, 0,5 mm in width, and 0,2 mm in height. Since SOA chips are made of III-V compound semiconductor materials and developed based on the technologies used for laser diodes (LDs), the basic physical mechanisms of generating optical gain in SOA chips are the same as those in LDs. Therefore, the population inversion inside the SOA chip is implemented by a forward current (I_F), and the input optical signals are amplified by the stimulated emission of photons in the active layer of the chip. The cross section of a typical active layer is 1,5 µm in width and 0,1 µm in thickness (height).

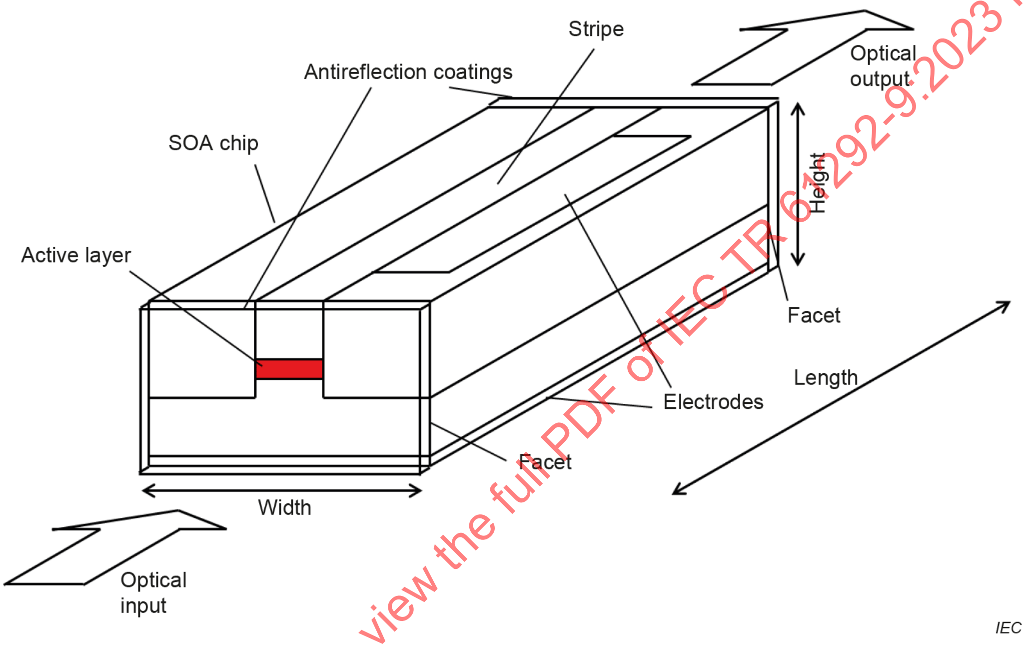


Figure 1 – Schematic diagram of the typical SOA chip

~~Figure 2 shows the gain dependency on I_F, which is injected into electrodes at the top and bottom of the SOA chip as shown in Figure 1. The gain of the SOA chip is obtained and adjusted by simply applying the current.~~ Figure 2 shows an example of the dependency of the SOA gain on the forward current I_F. The current is injected into the chip through electrodes at the top and bottom of the SOA chip, as shown in Figure 1. The gain of the SOA chip can be varied by adjusting the forward current. As shown in Figure 2, by increasing I_F to values greater than 150 mA, typical SOA chips can provide optical gain greater than 20 dB at an input optical power of around –20 dBm.

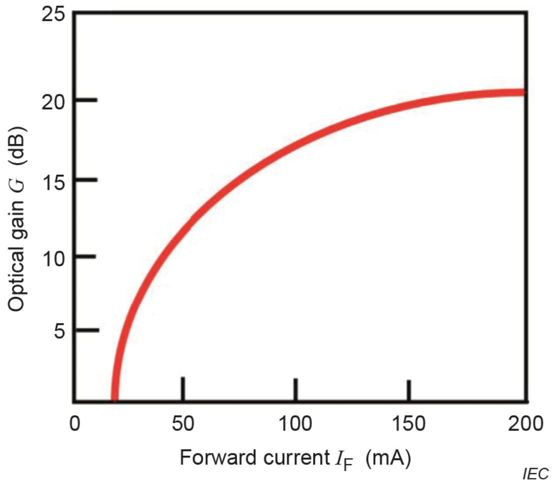
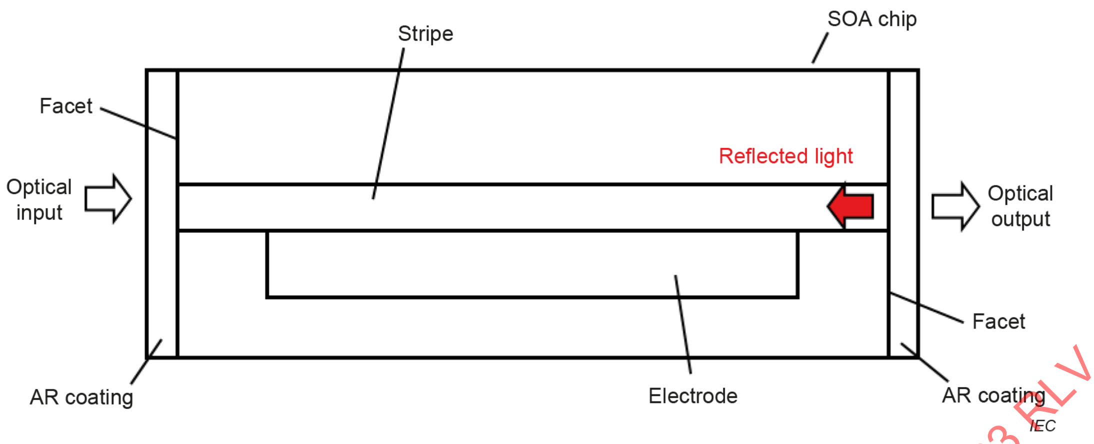
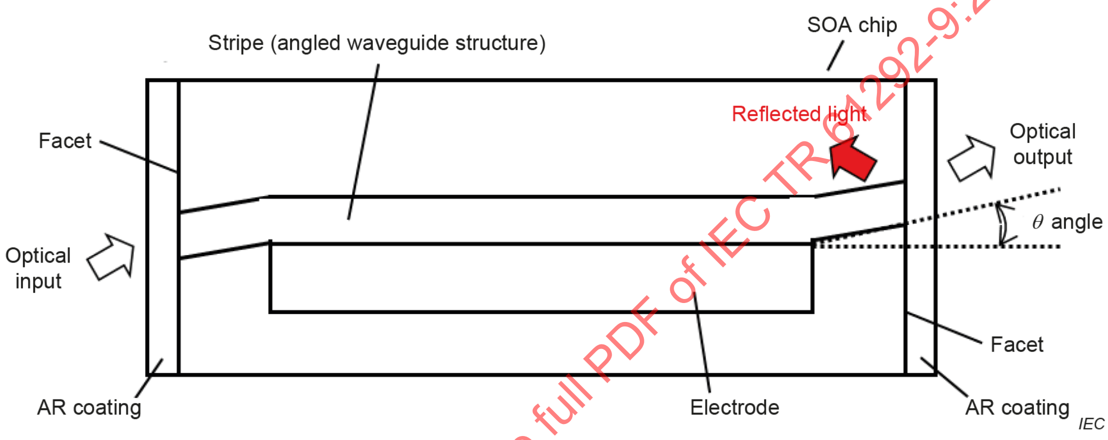


Figure 2 – Example of gain dependency of an SOA chip on forward current

Compared with LDs, the most distinctive feature of SOAs is that the SOA chip has anti-reflection (AR) coatings on both facets to avoid optical feedback between the facets. Since semiconductor materials have a much higher refractive index (> 3 is typical) than air, a facet without anti-reflection coating has a reflectivity of 30 % or above. This feature is suitable for establishing a laser cavity but not for the SOA chip, for which ~~requires~~ the facet has to have a reflectivity of less than 0,1 % over a wavelength range of greater than 30 nm. To achieve such a low reflectivity, AR coatings are employed on both facets of the SOA chip, as shown in Figure 3. Figure 3 a) and Figure 3 b) show schematic top views of a conventional SOA chip and an SOA chip with an angled waveguide structure, respectively. As shown in Figure 3 a), a conventional SOA chip has a straight stripe, which is normal to the two facets where AR coating is applied. The AR coating consists of a multiple-layer thin film. ~~Each thickness (a quarter wavelength, for example) of the film is controlled within ±4 %. The residual reflectivity will cause intra-cavity interference between the facets, which leads to gain ripple or laser oscillation. This is because the reflected light is easily coupled with the multiple reflections between the facets, since the angle (θ) between the stripe and the facet is 90°.~~ The thickness (e.g., quarter wavelength) of each film layer is controlled to within ±4 %. The residual reflectivity will cause intra-cavity interference between the facets, which leads to gain ripple or even laser oscillation. When the angle θ between the active stripe layer and the facet is 90°, the reflected light is readily coupled back into the stripe, thus leading to multiple reflections between the facets. One of the best ways to suppress intra-cavity feedback is the introduction of an angled waveguide structure, as shown in Figure 3 b). The reflected light cannot ~~be coupled by~~ encounter significant multiple reflections when using an angled stripe with $\theta = 7°$. This approach ~~enables the SOA chip to have a low facet reflectivity of~~ reduces the facet reflectivity to about 0,2 %, and to less than 0,1 % when combined with AR coatings.



a) **Conventional SOA chip**



b) **SOA chip with angled waveguide structure**

Figure 3 – Schematic top view of a typical SOA chip with and without an angled waveguide structure

Another specific feature of SOAs is that the gain wavelength band of SOA chips can be varied by ~~only~~ changing the composition of the semiconductor materials using mature LD technologies (i.e., by a band engineering technique). For example, long-wavelength (1 300 nm to 1 600 nm) SOA chips ~~have~~ typically use an InGaAsP active layer on an InP substrate, and the peak wavelength of the gain is adjusted by changing the ~~respective~~ relative concentrations of In, Ga, As and P in the InGaAsP layer. The typical gain wavelength ~~band~~ range of SOA chips is greater than 40 nm.

Another specific feature of SOA chips is ~~their integration~~ that they can be integrated with other semiconductor devices, such as tuneable LDs, electro-absorption modulators and passive waveguides, on a single chip. These integrated SOAs are used, for example, as booster amplifiers in tuneable LDs and line amplifiers (loss compensators) in photonic integrated circuits (PICs).

~~In summary, SOAs have completely different physical mechanisms for amplification and for the configuration of the device compared to OFAs.~~

~~SOA modules~~

In summary, SOAs have very different physical mechanisms for amplification and, hence, device configuration than conventional optical fibre amplifiers (OFAs).

Figure 4 shows the schematic top view of the SOA module. An SOA chip, a TEC, and optical lenses ~~may~~ can be assembled in a butterfly package which has fibre pigtails for the input and output ports. This is the most common package for SOA modules and its size is almost the same as that of 14-pin butterfly LD modules. The use of optical isolators (input and/or output) ~~may depend~~ depends on the application. For example, optical isolators are not employed in SOA modules for bidirectional amplification. The TEC is used to stabilize the temperature of the SOA chip, since more than 100 mA of electric current injected into the SOA chip will cause significant heating inside the chip ~~to~~, which can affect its polarization characteristics. Similar to LD modules, SOA modules are also hermetically sealed with N_2 gas.

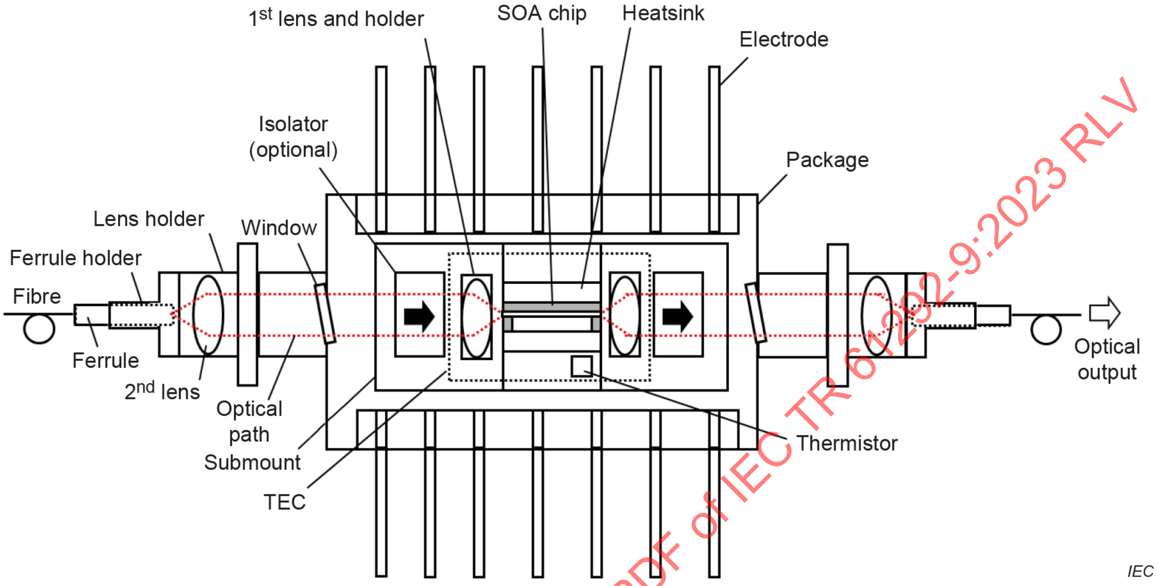


Figure 4 – Schematic top view of a typical SOA module

4.2 Gain ripple

4.2.1 General

Optical feedback inside the SOA chip, ~~which is the~~ resulting from residual reflections ~~from~~ at the chip facets, ~~may~~ can lead ~~to~~ round-trip resonances when an input optical signal is launched into the chip, as shown in Figure 5.

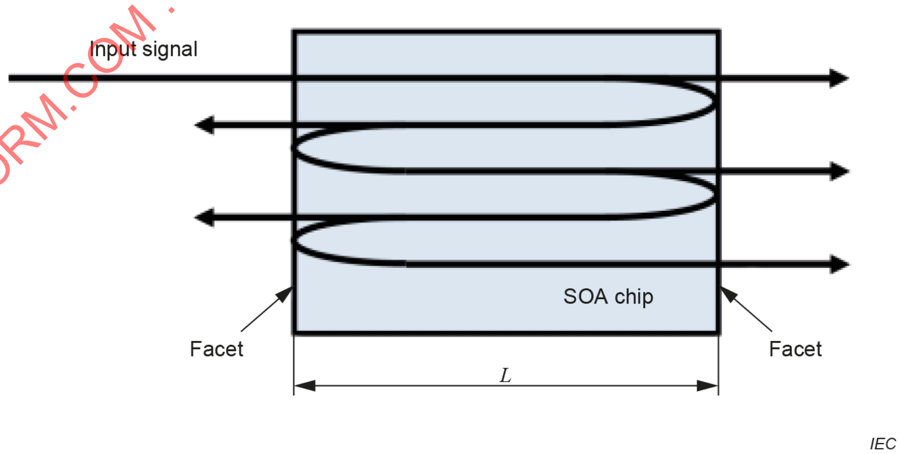


Figure 5 – Schematic diagram of the optical feedback inside the SOA chip

The amplified light from the various round-trip paths ~~will~~ can interfere constructively or destructively depending on the wavelength of the signal light. As a result, the SOA gain becomes wavelength dependent, as shown in Figure 6. This gain dependence on wavelength is called gain ripple~~, as shown in Figure 6~~.

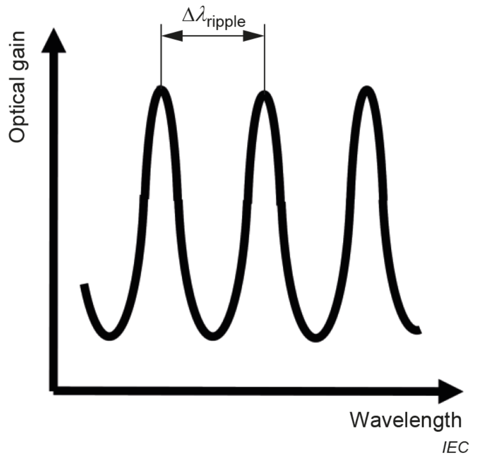


Figure 6 – Schematic diagram of gain ripple

With chip gain G and facet reflectivity R, the peak-to-peak amplitude of the gain ripple ΔG_{ripple} is given by Formula (1).

$$\Delta G_{ripple} = \frac{(1+G\times R)^2}{(1-G\times R)^2} \quad (1)$$

At signal wavelength λ, chip length L, and effective refractive index n_{eff}, the period of the gain ripple $\Delta\lambda_{ripple}$ ~~is derived~~ can be calculated from Formula (2).

$$\Delta\lambda_{ripple} = \frac{\lambda^2}{2 n_{eff} L} \quad (2)$$

At λ = 1 550 nm, for example, $\Delta\lambda_{ripple}$ is approximately 0,29 nm for an SOA chip with n_{eff} = 3,4 and L = 1,2 mm. Since an SOA ~~chip has the birefringence between the parallel transverse electric (TE) and orthogonal transverse magnetic (TM) directions to the chip substrate~~ waveguide typically exhibits birefringence between the transverse electric (TE) and orthogonally polarized transverse magnetic (TM) waves (relative to the chip substrate), $\Delta\lambda_{ripple}$ depends on the polarization ~~mode~~ state of the input light.

4.2.2 Theoretical calculation of gain ripple

4.2.2.1 SOA gain and gain ripple

Figure 7 shows the simplified model of a Fabry-Perot type SOA, which represents a typical SOA structure of length L and power reflectivities R_1 and R_2, respectively.

Assuming a uniform gain profile, the output electric field E_{out} in the presence of multiple reflections in the SOA cavity is given by Formula (3).

$$\begin{aligned} E_{\text{out}} &= \sqrt{(1-R_1)(1-R_2)G_s}\, E_{\text{in}} \exp(-j\beta_z L) \\ &\times \left[1+\sqrt{R_1 R_2}\, G_s \exp(-2j\beta_z L) + R_1 R_2\, G_s^2 \exp(-4j\beta_z L) + \cdots \right] \\ &= \frac{\sqrt{(1-R_1)(1-R_2)G_s}\, E_{\text{in}} \exp(-j\beta_z L)}{1-\sqrt{R_1 R_2}\, G_s \exp(-2j\beta_z L)} \end{aligned} \quad (3)$$

where

E_{in} is the amplitude of the input optical signal (E_{input} in Figure 1);

G_s is the single pass power gain;

β_z is the (longitudinal) propagation constant of the field in the cavity.

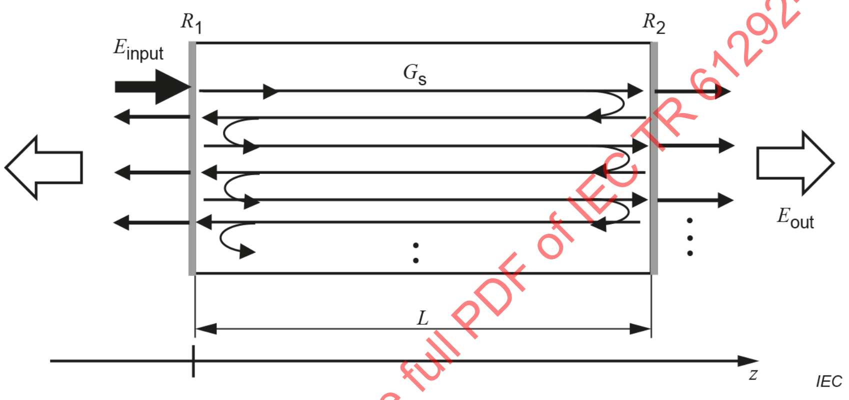


Figure 7 – Illustrated model of a Fabry-Perot type SOA

Then the overall SOA gain G is given by Formula (4).

$$G = \left|\frac{E_{\text{out}}}{E_{\text{input}}}\right|^2 = \frac{(1-R_1)(1-R_2)G_s}{\left(1-G_s\sqrt{R_1 R_2}\right)^2 + 4G_s\sqrt{R_1 R_2}\sin^2(\beta_z L)} \quad (4)$$

Depending on the value of $\beta_z L$, the SOA gain G calculated from Formula (4) varies between maximum and minimum values. When $\sin^2(\beta_z L)$ is zero in Formula (4), the wavelength of the input signal is equal to a multiple of the cavity resonance frequency, and G assumes its maximum value G_{max}, which is given by Formula (5).

$$G_{\text{max}} = \frac{(1-R_1)(1-R_2)G_s}{\left(1-G_s\sqrt{R_1 R_2}\right)^2} \quad (5)$$

In contrast, G is minimum when $\sin^2(\beta_z L)$ is equal to 1, which represents a phase mismatch of π between the input signal and the cavity resonance frequency. The minimum gain G_{min} is given by Formula (6).

$$G_{min} = \frac{(1-R_1)(1-R_2)G_s}{\left(1+G_s\sqrt{R_1 R_2}\right)^2} \tag{6}$$

The gain ripple ΔG_{ripple} is defined as the ratio of G_{max} to G_{min}, which can be readily calculated from Formulae (5) and (6), as shown in Formula (7).

$$\Delta G_{ripple} = \frac{G_{max}}{G_{min}} = \frac{\left(1+G_s\sqrt{R_1 R_2}\right)^2}{\left(1-G_s\sqrt{R_1 R_2}\right)^2} \tag{7}$$

4.2.2.2 SOA gain ripple derivation from ASE spectrum measurement

If there is no optical input signal, the output of an SOA is ASE light only. Figure 8 illustrates this situation for the same Fabry-Perot structure as shown in Figure 1, having length L, power reflectivities R_1 and R_2, and single pass power gain G_s. The only difference to Figure 1 is the absence of an optical input signal.

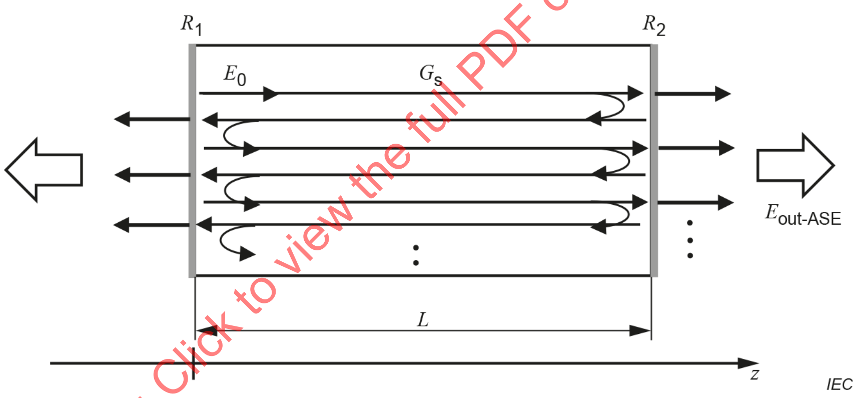


Figure 8 – Illustrated model of ASE output from an SOA

Similar to the case discussed in 4.2.2.1, the output electric field of the ASE, $E_{out-ASE}$, is impacted by multiple reflections in the SOA cavity. This can be calculated by assuming a uniform gain profile.

Letting E_0 denote the amplitude of the initial ASE electric field, the ASE output field $E_{out-ASE}$ is given by Formula (8).

$$\begin{aligned} E_{out-ASE} &= \sqrt{(1-R_2)G_s}\, E_0 \exp(-j\beta_z L) \\ &\times\left[1+\sqrt{R_1R_2}\, G_s \exp(-2j\beta_z L)+R_1R_2\, G_s^2 \exp(-4j\beta_z L)+\cdots\right] \\ &= \frac{\sqrt{(1-R_2)G_s}\, E_0 \exp(-j\beta_z L)}{1-\sqrt{R_1 R_2}\, G_s \exp(-2j\beta_z L)} \end{aligned} \tag{8}$$

Then the ASE output power is given by Formula (9).

$$\left|E_{\text{out-ASE}}\right|^2 = \frac{(1-R_2)G_s E_0^2}{\left(1-\sqrt{R_1 R_2}\,G_s\right)^2 + 4\sqrt{R_1 R_2}\,G_s \sin^2(\beta_z L)} \tag{9}$$

Moreover, the ASE gain G_{ASE} is given by Formula (10).

$$G_{\text{ASE}} = \left|\frac{E_{\text{out-ASE}}}{E_0}\right|^2 = \frac{(1-R_2)G_s}{\left(1-G_s\sqrt{R_1 R_2}\right)^2 + 4G_s\sqrt{R_1 R_2}\sin^2(\beta_z L)} \tag{10}$$

Similar to the SOA signal gain G, discussed in 4.2.2.1, the ASE gain G_{ASE} in Formula (10) varies between a maximum value $G_{\text{ASE-max}}$ and a minimum value $G_{\text{ASE-min}}$, depending on the value of $\beta_z L$. $G_{\text{ASE-max}}$ and $G_{\text{ASE-min}}$ are given by Formulae (11) and (12).

$$G_{\text{ASE-max}} = \frac{(1-R_2)G_s}{\left(1-G_s\sqrt{R_1 R_2}\right)^2} \tag{11}$$

$$G_{\text{ASE-min}} = \frac{(1-R_2)G_s}{\left(1+G_s\sqrt{R_1 R_2}\right)^2} \tag{12}$$

Hence, the ripple $\Delta G_{\text{ripple-ASE}}$ observed in the ASE gain is given by Formula (13).

$$\Delta G_{\text{ripple-ASE}} = \frac{G_{\text{ASE-max}}}{G_{\text{ASE-min}}} = \frac{\left(1+G_s\sqrt{R_1 R_2}\right)^2}{\left(1-G_s\sqrt{R_1 R_2}\right)^2} \tag{13}$$

A comparison shows that Formula (13) is identical to Formula (7), which was derived from signal gain calculations. It follows that the gain ripple of an SOA can be determined from a ripple measurement in the ASE output spectrum measurement, even if the gain characteristics of the SOA are unknown.

However, Formulae (3) and (4) are valid only if the value of G_s is less than $1/\sqrt{R_1 R_2}$. In addition, the calculations above assume a uniform gain profile in the SOA. If the device and/or measurement conditions do not meet these criteria, the gain ripple cannot be determined from the ASE spectrum.

4.3 Polarization dependent gain (PDG)

4.3.1 General

The PDG of SOAs is mainly caused by the difference in the confinement factors of the TE and TM modes. Generally, the cross-section of the active layer has an anisotropic ~~structure~~ geometry because the thickness of the active layer (e.g., 0,1 µm) is smaller than its width (e.g., 1,5 µm). This results in a larger confinement factor for the TE mode (Γ_{TE}) than for the TM mode (Γ_{TM}), which means that the gain for the TE mode is larger than that for the TM mode.

PDG is one of the most significant characteristics of SOA modules. The total polarization dependence of the single pass gain in SOAs, PDG_{total}, is known to be the sum of the polarization dependence of the active layer gain (PDG_{active}) in SOA chips and the polarization dependence of the coupling efficiency (PDCE) between fibre and facet at both input and output ports of the SOA module.

In general, SOA chips have an elliptical mode field, so the PDCE is not zero. Therefore, unless a specific design is implemented for the PDCE, SOA modules might have a certain amount of PDG_{total} even if the PDG_{active} is zero.

4.3.2 Polarization insensitive SOAs

4.3.2.1 General

As described in 4.3.1, the polarization sensitivity of SOA chips is mainly caused by the difference between Γ_{TE} and Γ_{TM}. To achieve polarization insensitivity, ~~decreasing or compensation of the difference will be needed~~ it is necessary to decrease or compensate this difference. It has been reported that the techniques outlined in 4.3.2.2 and 4.3.2.3 can yield PDG_{total} of less than 0,5 dB.

4.3.2.2 Bulk active layer with square cross-section waveguide structure

To reduce the difference between Γ_{TE} and Γ_{TM}, the thickness of the bulk active layer of the SOA chip is increased to obtain an isotropic cross-section waveguide structure in the active layer. This structure enables SOA chips to have not only low PDG_{active} but also low PDCE. However, the isotropic waveguide structure results in a ~~high~~ large total confinement factor, which in turn results in low saturation output power. The saturation output power is defined as the output power at which the gain decreases by 3 dB from the linear regime.

4.3.2.3 Active layer with strained multiple quantum wells (MQWs)

To compensate for the difference in Γ_{TE} and Γ_{TM}, the TM gain coefficients ~~will~~ can be controlled by using strained MQWs in the active layer. The introduction of tensile strained MQWs into the active layer leads to a higher TM gain coefficient than the TE gain coefficient. This technique enables SOA chips to have an overall reduction in PDG_{total}. Since the total confinement factor of this structure is smaller than that in an isotropic bulk active layer, the saturation output power is higher compared with SOA chips with isotropic bulk active layers.

4.4 Noise figure (NF)

Generally, the noise figure (NF) of SOAs depends on the population inversion factor n_{sp} and the coupling efficiency between the input fibre and the SOA. If the coupling efficiency is 100 % and n_{sp} = 1, the noise factor is equal to $2n_{sp}$ and consequently ~~resulted in~~ equal to 2, ~~namely~~ yielding an NF of 3 dB in the ideal case. The n_{sp} of practical SOA chips is ~~more~~ higher than unity because of the incomplete population inversion and the internal optical loss. In addition, the optical coupling between the SOA chip facet and fibre is achieved by using a two-lens system, which leads to the optical coupling loss of typically a few decibels because of the anisotropic structure of the active layer of the SOA chips (e.g., 1,5 µm in width and 0,1 µm in thickness). Therefore, the NF of SOA modules is typically more than 6 dB.

Since the NF depends on the coupling efficiency at the input, the NF of SOA modules with PDG_{active} = 0 have high polarization dependence unless PDG_{total} is zero.

4.5 Lifetime of carriers

The lifetime of carriers in SOA chips is in the order of nanoseconds, leading to effects such as cross gain modulation (XGM) and a type of signal distortion called the "pattern effect" when used in gigabit-class optical signal systems.

4.6 Nonlinear effects

The SOA has nonlinear effects, such as cross phase modulation (XPM) and four-wave mixing (FWM). These effects are mainly caused by the carrier dynamics of SOA chips and lead to additional applications including wavelength conversion and wavelength demultiplexing. Since this document focuses on the amplification application, further details of these nonlinear effects are not addressed in this document.

5 Measurement of SOA output power and PDG

5.1 Narrow-band versus broadband light source

It is usually difficult to measure SOA output power and gain using a narrow-band light source for the input signal because of the gain ripple. Gain ripple causes measurement errors in optical output power and polarization dependence. Since signal gain depends on temperature, input optical power, signal wavelength and forward current, measurement results ~~may suffer from the lack of reproducibility~~ are sometimes not reproducible. In this case, the use of a wide-band optical light source has advantages. By averaging the signal gain in the SOA over a wide wavelength range, the optical power or polarization dependence can be accurately estimated, because the influence of gain ripple on the measurement results is drastically reduced.

Figure 9 shows an example of the wavelength dependence of output power and polarization dependence ~~on the wavelength of the~~ for an SOA with a gain ripple of about 3 dB. The upper graph shows the optical power dependence on wavelength, measured by using a distributed feedback (DFB) LD as the input light source. The red and blue lines are the TE and TM mode gains of the SOA, respectively. The gain ripple is clearly observed because the DFB-LD has a linewidth much narrower than the period of the gain ripple. As shown in Figure 9, the amplitude of the gain ripple of the TE and TM modes are 3,2 dB and 3,0 dB, respectively, and the period of each mode is 0,8 nm and 0,7 nm, respectively. The bottom graph shows the PDG dependence on wavelength for the SOA. The green and black lines are for the DFB-LD and the amplified spontaneous emission (ASE) light source, respectively. Whereas the ~~use of~~ measurement with the DFB-LD showed a large PDG of more than ±2 dB, the PDG measured by using the ASE light source was as only 0,2 dB.

NOTE An ASE source is one example of a broadband light source.

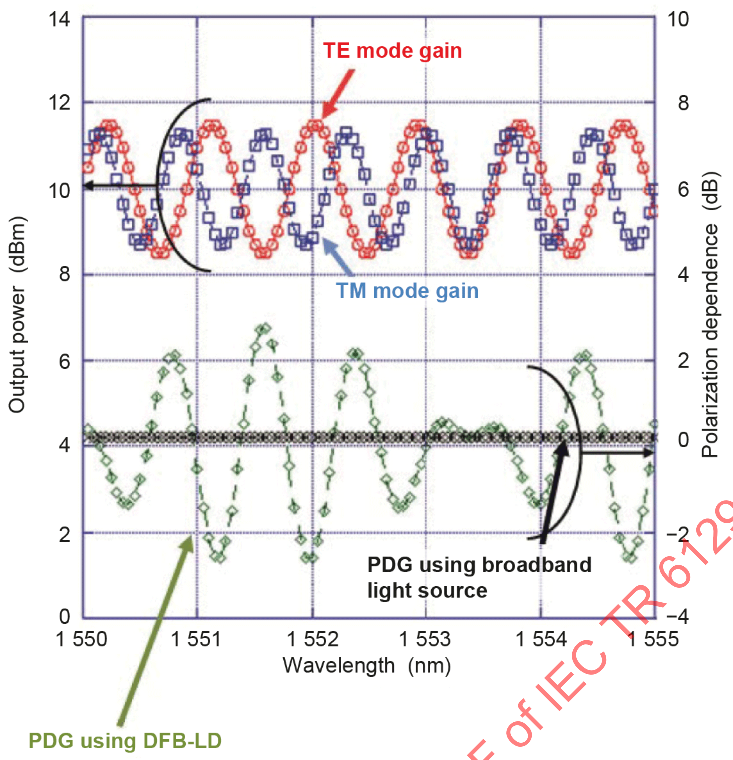


Figure 9 – SOA output power and PDG dependence on wavelength

The gain ripple can be estimated using an optical spectrum analyser. Since the gain ripple depends on several parameters, an accurate measurement is very difficult in terms of reproducibility. ~~Including the information on the wavelength (frequency) resolution of the analyzer is preferable in the test report of gain ripple.~~ It is good practice to document the wavelength (frequency) resolution of the analyser in the test report for the gain ripple measurement.

~~**5.2 Recommended set-up for output power and PDG measurements**~~

~~Subclause 5.2 describes a measurement method for output power and PDG of SOAs by using a broadband light source and describes how the results will be different from those using a narrow-band light source (DFB-LD).~~

~~Figure 8 shows a recommended measurement set-up for SOA modules that incorporates a broadband light source. The broadband light source emits a continuous wave with a wavelength bandwidth (the full width at half maximum, FWHM), which shall be wider than a gain ripple period (more than five-times wider if possible) of the SOA module under test. For example, superluminescent diodes (SLDs) and the ASE generated from OFAs or SOA modules are applicable as a broadband light source. Note that the ASE from the light source shall be a single polarization mode to measure the polarization dependence of the SOA characteristics. Thus, polarization maintaining OFAs, for example, with a polarization extinction ratio of larger than 15 dB are applicable. Alternatively, to enhance the ratio, the polarizer (POL) is used between the broadband light source and the band pass filter 1 (BPF1).~~

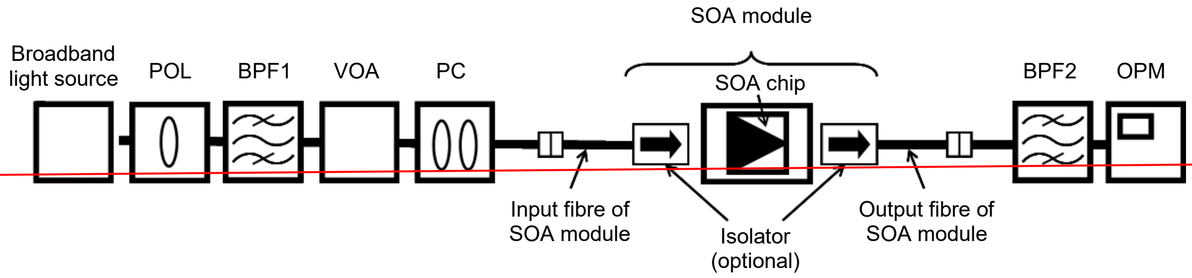


Figure 8 – Recommended measurement set-up for optical power and PDG of SOA modules

In Figure 8, the BPF1 is used to reduce the bandwidth of the broadband light source, and the reduced bandwidth should be more than five times the period of the SOA module under test. Since there are no guarantees that the gain spectra of SOA and that of the input broad band light source are the same, spectral filtering is necessary. The bandwidth of the filter should be carefully chosen to obtain accurate measurement results. A variable optical attenuator (VOA) and polarization controller (PC) are employed to adjust the input power and the state of polarization, respectively. Another BPF (BPF2), which is inserted between the SOA and an optical power meter (OPM), is required to have the same bandwidth as the BPF1. As the SOA module under test has fibre pigtails, the measurement equipment is interconnected by using fibres.

On the other hand, in Figure 9, which shows the recommended measurement set-up for SOA chips, the input and output lensed fibres are used for optical coupling with input and output of the SOA chip, respectively.

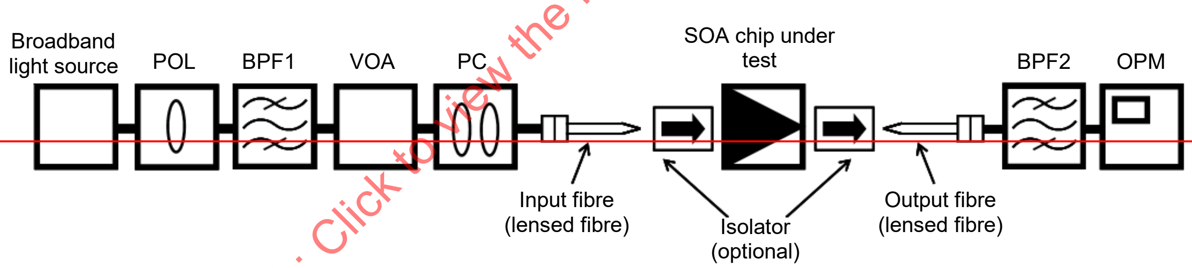


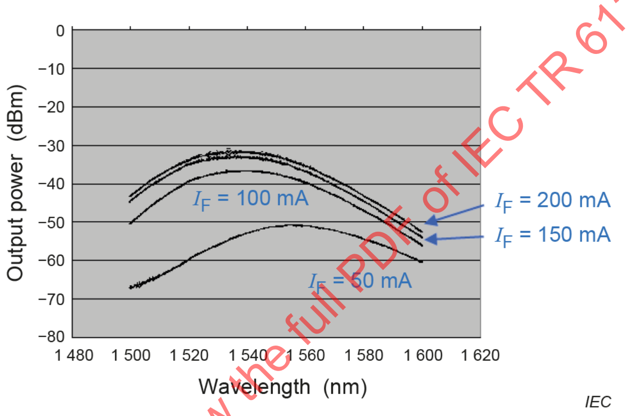
Figure 9 – Recommended measurement set-up for optical power and PDG of SOA chips

5.2 Examples of measurement results obtained by using the recommended set-up

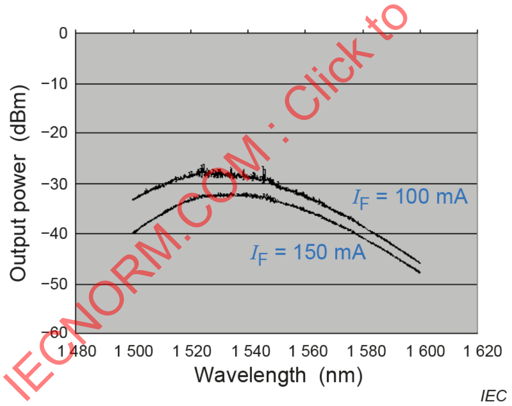
In 5.3, the advantage of using a broadband light source is described. Figure 10 a), Figure 10 b), and Figure 10 c) show the optical power spectra of three different SOA chips at various forward currents (I_F), and amplitude of the gain ripple. The period of the gain ripple of these SOA chips is less than 0,5 nm. In the output power and PDG measurements of the SOA chips, two input light sources were used for the comparison. One was the DFB-LD with a linewidth of approximately 2 MHz (16 fm in wavelength), and the other was the ASE generated from the polarization maintaining EDFA. The peak wavelength of both light sources was 1 540 nm, and the polarization extinction ratio of the ASE emitted from the EDFA was 20 dB. The measurement set-up using the EDFA was the same as shown in Figure 9, and the bandwidth of the BPF1 and BPF2 was set to be 5 nm, which was more than ten times the gain ripple period of the SOAs. The BPF1 was omitted when the DFB-LD was used as the input light source, and the bandwidth of the BPF2 was set to be 1 nm. The VOA adjusted the input power of both light sources to –20 dBm, and the polarization mode was set to be the TE or TM modes with the PC.

5.2 compares optical power and PDG measurement results obtained by using a broadband light source with those obtained by using a narrow-band wavelength-tuneable light source.

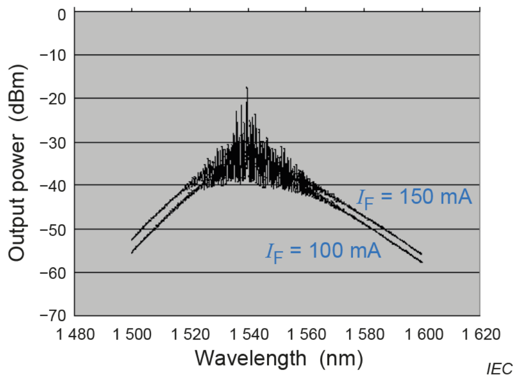
Figure 10 a), Figure 10 b), and Figure 10 c) show the optical power spectra of three different SOA chips at various forward currents I_F and gain ripple amplitude. The period of the gain ripple of these SOA chips is less than 0,5 nm. In the output power and PDG measurements of the SOA chips, two input light sources were used for the comparison. One light source was a DFB-LD with a linewidth of approximately 2 MHz (i.e., 16 fm in wavelength), and the other light source was the ASE generated by a polarization maintaining EDFA. The peak wavelength of both light sources was 1 540 nm, and the polarization extinction ratio of the ASE emitted from the EDFA was 20 dB. For the measurement set-up using the EDFA, a polarizer (POL) and an optical band pass filter (BPF) was used instead of the narrow-band wavelength-tuneable optical source employed in the measurement set-up described in IEC 61290-1-1. The bandwidth of the BPF and the optical spectrum analyser was set to 5 nm, which was more than ten times the gain ripple period of the SOAs. The BPF was omitted when the DFB-LD was used as the input light source, and the bandwidth of the BPF2 was set to 1 nm. A VOA was used to adjust the input power of both light sources to –20 dBm, and the polarization mode was set to be either TE or TM using a polarization controller (PC).



a) SOA chip sample 1 with negligibly small gain ripple at I_F = 100 mA



b) SOA chip sample 2 with a gain ripple of about 1 dB at I_F = 100 mA



c) SOA chip sample 3 with a gain ripple of more than 10 dB at I_F = 100 mA

Figure 10 – Optical power spectra of three different SOA chips

Figure 11, Figure 12, and Figure 13 show the measurement results obtained with the SOA chip samples 1, 2 and 3, respectively. In these figures, the lower graph shows the output power of the TE and TM modes as a function of I_F, and the upper graph shows the PDG dependence on I_F. For comparison, the red and black lines ~~are~~ represent the measurement results obtained with the ASE light source and the DFB-LD, respectively.

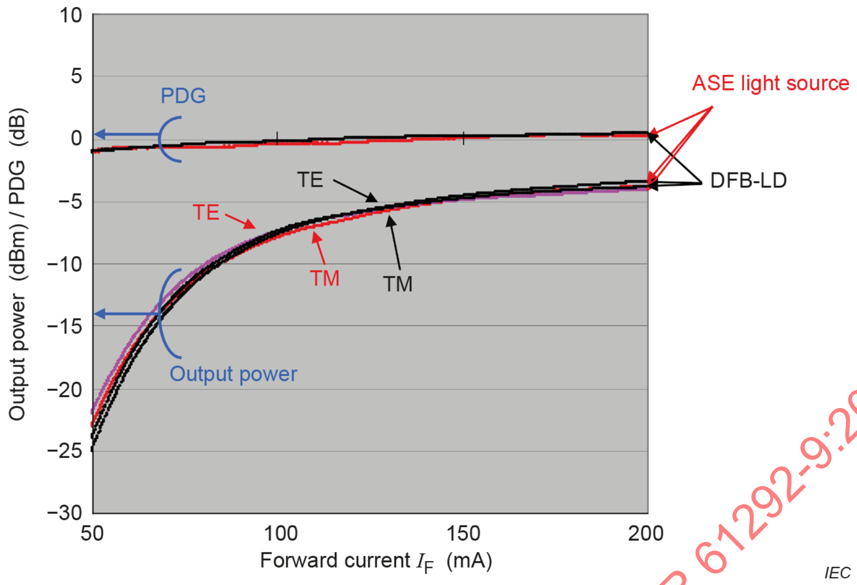


Figure 11 – Output power and PDG of SOA chip sample 1 as a function of I_F

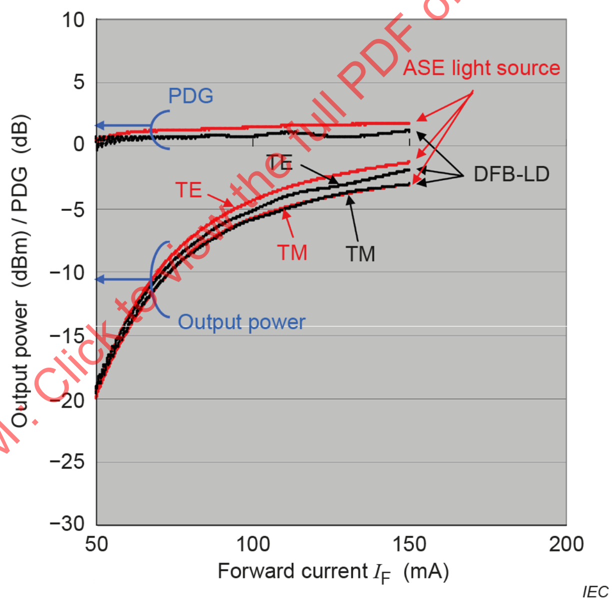


Figure 12 – Output power and PDG of SOA chip sample 2 as a function of I_F

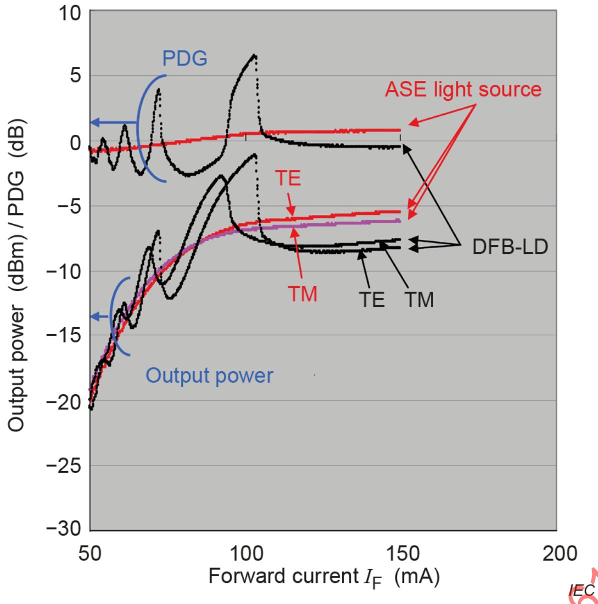


Figure 13 – Output power and PDG of SOA chip sample 3 as a function of I_F

~~As shown in Figure 11, the difference in the results between the ASE light source and DFB-LD was almost negligible due to the small gain ripple of the SOA chip (sample no. 1). However, as shown in Figure 12, the PDG measured by using the ASE light source was about 1,0 dB larger than when the DFB-LD was used. This difference was caused by the 1,0 dB gain ripple of the SOA chip (sample no. 2). Even if the gain ripple is as large as 10 dB, this method is applicable, as shown in Figure 13. When the DFB-LD was used, the output power and the PDG extremely depended on the I_F due to the ripple. For example, the PDG was as large as 6 dB at I_F = 100 mA while almost 0 dB at I_F = 110 mA. On the other hand, the PDG obtained by using the ASE light source was still stable at the whole range of I_F because of the averaged optical power over the sufficient bandwidth of 5 nm.~~

~~In summary, an SOA that has x dB amplitude of the gain ripple results in variation of the PDG within ±x dB when a narrow-band light source is used for the measurement. For example, 3 dB amplitude of the gain ripple leads to ±3 dB variation of the PDG due to the difference of the gain ripple period between the TE and TM modes, as shown in Figure 7. Moreover, even if the amplitude of the gain ripple of the SOA is as small as 0,5 dB, it is still not practical to measure the PDG by using a narrow-band light source because ±0,5 dB variation of the PDG is comparable to the gain ripple. Thus, to avoid influence by the gain ripple, the output power and PDG should be measured by using a broadband light source. In this case, the amplitude of the gain ripple of the SOA should be noted along with the measured results of the output power and PDG.~~

~~However, a narrow-band light source should be applicable for the gain and saturation output power measurements if the gain ripple of SOAs is negligibly small. For example, if the amplitude of the gain ripple of the SOA is as small as 0,5 dB, the measurement error when the narrow-band light source is used would be ±0,25 dB, which is much smaller than the typical gain of > 20 dB. Thus, if the users can accept this error, a narrow-band light source will be applicable for the gain and saturation output power measurements.~~

In Figure 11, the difference between the results obtained with the ASE light source and the DFB-LD was negligible due to the small gain ripple of SOA chip sample 1. However, in Figure 12, the PDG measured with the ASE light source was about 1,0 dB larger than that measured with the DFB-LD. This difference was caused by the 1,0 dB gain ripple of SOA chip sample 2. Even if the gain ripple was as large as 10 dB, the measurements with the ASE light source produced smooth and reliable results, as shown in Figure 13 for SOA chip sample 3. When the DFB-LD was used, the measured output power and PDG varied largely with I_F due to the large gain ripple. For example, the PDG was as large as 6 dB at I_F = 100 mA while almost 0 dB at I_F = 110 mA. On the other hand, the PDG obtained by using the ASE light source was constant over the whole range of I_F, because of the optical power was averaged over a sufficiently large bandwidth of 5 nm.

In summary, an SOA with a gain ripple amplitude of x-dB amplitude can show variations of ±x dB in the PDG measurements when a narrow-band light source is used. For example, a gain ripple amplitude of 3 dB can lead to ±3 dB variations in the measured PDG due to the difference of the gain ripple period between the TE and TM modes, as shown in Figure 9. Moreover, even if the amplitude of the gain ripple of the SOA is as small as 0,5 dB, it is still not advisable to measure the PDG with a narrow-band light source, because of the ±0,5 dB uncertainty in the PDG measurements. Thus, to avoid the influence of gain ripple, it is better to measure output power and PDG with a broadband light source. In this case, the amplitude of the gain ripple of the SOA can be noted along with the measured results of the output power and PDG.

However, a narrow-band light source can be used for measuring the gain and saturation output power of SOAs if the gain ripple is sufficiently small. For example, if the amplitude of the gain ripple of the SOA was as small as 0,5 dB, the measurement error in the gain measurement would be ±0,25 dB when a narrow-band light source is used, which is much smaller than the typical SOA gain of > 20 dB. Thus, if this error is acceptable to the user, a narrow-band light source can be used for the gain and saturation output power measurements.

Annex A
(informative)

Applications of SOAs

A.1 General

Currently, discrete SOA modules are not commonly employed in commercial ~~optical network systems~~ fibre optic communication networks. This is because several characteristics of SOAs, such as PDG and NF, usually do not meet the system requirements. Also, SOAs are not applicable for systems that require a large saturation output power, because the gain length of SOAs is typically as short as 1,5 mm. On the other hand, since SOA chips can be integrated with other semiconductor devices, integrated SOA chips are widely used in PICs as boosters and line amplifiers. Annex A briefly reviews current and proposed applications of discrete SOA modules and integrated SOA chips.

A.2 Polarization mode of SOAs

The polarization mode of an SOA chip is typically designed by taking ~~the~~ its intended application into account. Generally, integrated SOA chips used as booster amplifiers for LDs are TE-polarized because the LDs emit TE-polarized light. ~~However, discrete SOA modules used as line amplifiers should be polarization independent because the polarization mode will be randomly changed by propagation in the fibre in optical links. SOAs for a pre-amplifier should be discrete modules because the SOA modules need an optical filter to reduce the ASE noise between the SOA modules and photodiodes (PDs). To receive the signal light with various polarization modes, the SOA modules used as a pre-amplifier should be polarization independent.~~ However, discrete SOA modules used as line amplifiers are generally polarization independent because the input polarization state to the SOA changes randomly when light propagates through an optical fibre link. Likewise, polarization-independent SOAs are used as pre-amplifiers in optical receivers, where the input light can be in various polarization states. In this application, the SOAs are typically discrete modules, because they often employ an optical filter after the SOA module and before the subsequent photodiodes (PDs) to reduce the ASE noise.

A.3 Reach extender for GPON

Recently, the use of SOA modules was proposed as one example of OA-based reach extenders for GPON in ITU-T Recommendation G.984.6. The reach extender is incorporated into the fibre link between the optical line termination (OLT) and optical network unit (ONU) to increase the reach to 60 km in both the upstream (λ = 1 310 nm) and downstream (λ = 1 490 nm) directions. The SOA chips can be easily adapted to both wavelengths by changing the composition of the semiconductor materials. For this application, an SOA chip, a TEC, and optical lenses ~~may~~ can be assembled in a butterfly package that has two fibre pigtails for the input and output ports, as shown in Figure 4. When used as a line amplifier in GPON, polarization independent SOA modules ~~may be~~ are typically utilized ~~for this application~~.

A.4 Pre-amplifier in transceivers for 100 Gbit Ethernet

In the IEEE 802.3ba task force, installing an SOA module as a pre-amplifier into 40 km-100 Gigabit Ethernet transceivers was proposed. The multi-source agreement (MSA) defined them as 100G form factor pluggable (CFP) transceivers as described in CFP MSA Hardware Specification Revision 1.4.

Figure A.1 shows the schematic diagram of the receiver section of SOA-incorporated CFP transceivers.~~ The input signal light in a single-mode fibre (SMF) is multiplexed by four wavelengths (λ1, λ2, λ3, and λ4) with the wavelength interval of about 5 nm in around 1 300 nm, and each wavelength has a signal bandwidth of about 25 Gbit/s. After the input port of the transceivers, the signal light launches into the SOA module.~~ The input signal light to a single-mode fibre (SMF) is composed of four multiplexed wavelengths (λ1, λ2, λ3, and λ4) within a wavelength band of about 5 nm around 1 300 nm, where each wavelength carries an information signal with a data rate of about 25 Gbit/s. After propagating through the fibre, the multiplexed signals are launched into an SOA module at the input port of the transceiver. Since the signal light is multiplexed, four wavelengths are simultaneously amplified by the SOA module. Then, the amplified signal light is demultiplexed into four individual optical signal lines by a 1:4 demultiplexer (DEMUX). The demultiplexed~~ signal lights~~ optical signals are converted to four 25 Gbit/s~~-4 channel~~ parallel electric signals by four PDs. The electric signals are amplified by transimpedance amplifiers (TIAs) and then converted to 10 Gbit/s 10-channel parallel signal lines by a 4:10 de-serializer.

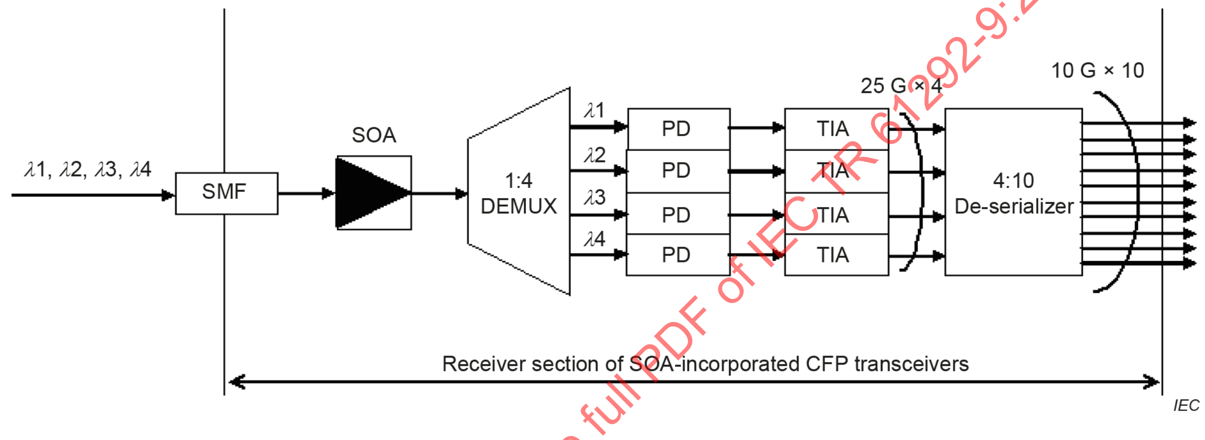


Figure A.1 – Schematic diagram of the receiver section of SOA-incorporated CFP transceivers

In this application, the SOA module is a butterfly package, which~~ may~~ can be installed between the input port and 1:4 DEMUX.~~ As a pre-amplifier, the SOA module shall be polarization independent.~~ In general, polarization independent SOAs are used as pre-amplifiers.

A.5 Monolithic integration of SOAs

~~Figure A.2 shows an example of the monolithic integration. Shown is a DFB-LDs-array wavelength tuneable LD, which consists of a DFB-LDs array, a multi-mode interference (MMI) device, and an SOA chip in one chip. In this PIC, the integrated SOA chip is used as the booster amplifier and amplifies a continuous wave light launched from the DFB-LDs array via the MMI device.~~ Figure A.2 displays an example of monolithic integration of an SOA with other optical components. The example shown is a wavelength tuneable LD that consists of an array of DFB-LDs, a multi-mode interference (MMI) device, and an SOA, all integrated in a single chip. In this PIC, the integrated SOA is used as a booster amplifier for the continuous-wave light generated by the various DFB-LDs array and combined in the MMI device. SOA integrated tuneable LDs are often used in tuneable optical transceivers, which are indispensable components in current telecommunication systems. Generally, the integrated booster SOA chips in tuneable LDs are polarization dependent (TE mode polarized) because the DFB-LDs emit TE polarized light. In other PICs,~~ if~~ where the polarization~~ mode~~ state of the input light to the integrated SOA~~ chips~~ is random,~~ the integrated SOA chips should be~~ polarization-independent SOAs are used.

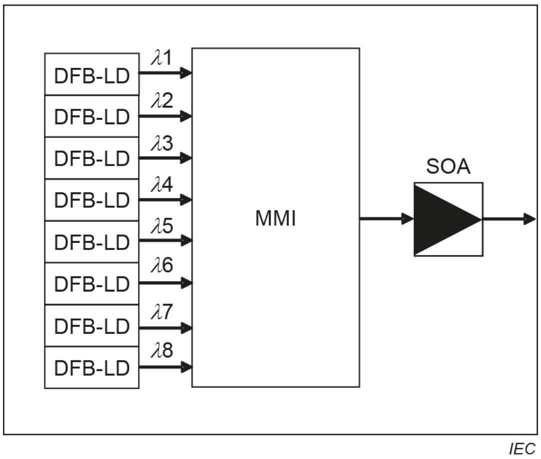


Figure A.2 – Schematic diagram of the DFB-LDs-array type wavelength tuneable LD

A.6 Reflective SOAs (RSOAs)

RSOAs have a high reflection mirror on one facet of the SOA and an anti-reflection coating on the other facet, while conventional SOA chips have anti-reflection coatings on both facets. This design can offer be used as an amplification module with a single pigtailed fibre for the optical inputs and outputs. The input light launches into the input/output port of the RSOA chip, and is amplified and reflected by the mirror. Then, the amplified light propagating along the opposite direction is amplified again inside the chip and is emitted from the input/output port. The input light enters the input/output port of the RSOA chip and is then amplified before it is reflected by the mirror. The reflected light, propagating in the opposite direction, is then further amplified in the chip before it is emitted from the input/output port.

Recently, RSOAs have attracted attention as a promising candidate for an optical transmitter of ONUs for seeded WDM-PON systems, as shown in Figure A.3. ITU-T G.698.3 defines and provides values for optical interface parameters of point-to-point seeded WDM applications. Since SOAs have a directmodulation bandwidth of approximately 2 GHz, RSOAs are considered suitable as reflective colourless amplifying modulators. In seeded WDM-PON systems, not only the signal light (downstream signal) but also the CW light of the seed light source are transmitted from the central office, and ONUs receive both signal and CW light. the received CW light in each ONU is fed into the RSOA, and then it is amplified and modulated by the RSOA. The modulated signal light is transmitted as the upstream signal from the ONU to the OLT in the central office. Recently, RSOAs have been identified as promising candidates for serving as optical transmitters in ONUs for seeded WDM-PON systems, as shown in Figure A.3. ITU-T G.698.3 defines and provides values for optical interface parameters of point-to-point seeded WDM applications. Since SOAs have direct-modulation bandwidths of approximately 2 GHz, RSOAs can be used as reflective, colourless amplifying modulators. In seeded WDM-PON systems, unmodulated CW light from a seed light source is transmitted from the central office OLT to the ONUs in addition to the modulated signal light (i.e., downstream signal). The ONUs receive both the modulated signal and the CW light. In each ONU, the received CW light is fed into an RSOA, which then amplifies and modulates the light. The modulated signal light is transmitted as the upstream signal from the ONU to the OLT in the central office.

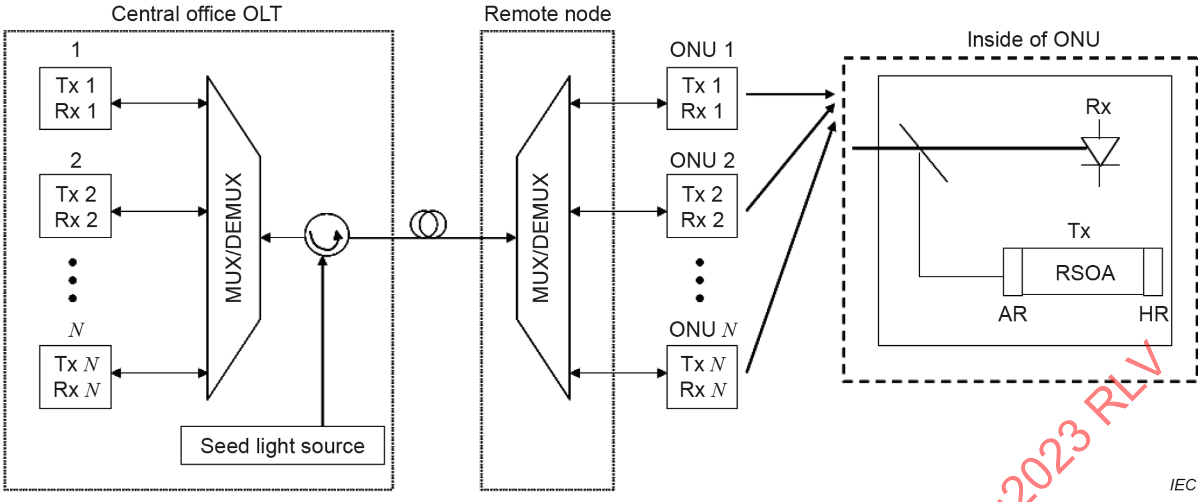


Figure A.3 – Schematic diagram of a seeded WDM-PON system

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IEC TR 61292-9

Edition 3.0 2023-01

TECHNICAL REPORT

colour inside

Optical amplifiers –
Part 9: Semiconductor optical amplifiers (SOAs)

IEC TR 61292-9:2023-01(en)

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INTERNATIONAL ELECTROTECHNICAL COMMISSION

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OPTICAL AMPLIFIERS –

Part 9: Semiconductor optical amplifiers (SOAs)

FOREWORD

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IEC TR 61292-9 has been prepared by subcommittee 86C: Fibre optic systems and active devices, of IEC technical committee 86: Fibre optics. It is a Technical Report.

This third edition cancels and replaces the second edition published in 2017. This edition constitutes a technical revision.

This edition includes the following significant technical changes with respect to the previous edition:

a) revised definitions for SOAs in 3.1;
b) added more theoretical background on gain ripple measurements using amplified spontaneous emission (ASE) spectrum in 4.3;
c) removed the formerly preferred set-up for output power and PDG measurements in Clause 5.

The text of this Technical Report is based on the following documents:

Draft	Report on voting
86C/1820/DTR	86C/1830/RVDTR

Full information on the voting for its approval can be found in the report on voting indicated in the above table.

The language used for the development of this Technical Report is English.

This document was drafted in accordance with ISO/IEC Directives, Part 2, and developed in accordance with ISO/IEC Directives, Part 1 and ISO/IEC Directives, IEC Supplement, available at www.iec.ch/members_experts/refdocs. The main document types developed by IEC are described in greater detail at www.iec.ch/publications.

A list of all parts in the IEC 61292 series, published under the general title *Optical amplifiers*, can be found on the IEC website.

The committee has decided that the contents of this document will remain unchanged until the stability date indicated on the IEC website under webstore.iec.ch in the data related to the specific document. At this date, the document will be

- reconfirmed,
- withdrawn,
- replaced by a revised edition, or
- amended.

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INTRODUCTION

Optical amplifiers (OAs) are essential components for fibre optic communication systems, where they serve as booster amplifiers, in-line amplifiers, and pre-amplifiers. Numerous standards have been published for OAs (e.g., the IEC 61290 series and IEC 61291 series). However, most of these standards focus on optical fibre amplifiers (OFAs) because these are commonly deployed in commercial fibre optic networks. Recently, semiconductor optical amplifiers (SOAs) have attracted attention for applications in Gbit passive optical networks (GPONs) and Gbit Ethernet (GbE) systems, which operate at line rates of 100 Gbit/s and beyond. SOA chips are as small as laser diodes (LDs) and are directly driven by an electrical current.

Although SOAs operating in the 1 310 nm or 1 550 nm wavelength bands have been extensively studied since the 1980s, SOAs have mostly been used in laboratories or in field trials. This is due to certain performance limitations of SOAs, such as gain ripple and polarization dependent gain (PDG). As a result, there are few IEC documents addressing SOAs. One exception is IEC TR 61292-3, which is a Technical Report on classification, characteristics, and applications of OAs including SOAs. However, IEC TR 61292-3 presents only general information on SOAs and does not contain detailed information on test methods for measuring the particular performance parameters of SOAs.

IEC 61290-1-1:2020 describes test methods for power and gain parameters of OAs, which includes a method for gain ripple measurements on SOAs. This document has been revised to harmonize its content with IEC 61290-1-1 and with IEC 61291-2.

This document provides more detailed descriptions of the specific features of SOAs, including information on gain ripple and PDG.

OPTICAL AMPLIFIERS –

Part 9: Semiconductor optical amplifiers (SOAs)

1 Scope

This part of IEC 61292, which is a Technical Report, describes the characteristic features of semiconductor optical amplifiers (SOAs), including the specific features of gain ripple and polarization dependent gain (PDG).

This document focuses on amplifying applications of SOAs. Other applications, such as modulation, switching and non-linear functions, are not covered.

Potential applications of SOAs, such as reflective SOAs (RSOAs) for the seeded wavelength division multiplexing passive optical network (WDM-PON), are reviewed in Annex A.

2 Normative references

The following documents are referred to in the text in such a way that some or all of their content constitutes requirements of this document. For dated references, only the edition cited applies. For undated references, the latest edition of the referenced document (including any amendments) applies.

IEC 61291-1:2018, *Optical amplifiers – Part 1: Generic specification*

IEC 61291-2:2016, *Optical amplifiers – Part 2: Single channel applications – Performance specification template*

3 Terms, definitions, abbreviated terms and symbols

3.1 Terms and definitions

For the purposes of this document, the terms and definitions given in IEC 61291-1:2018, IEC 61291-2:2016, and the following apply.

ISO and IEC maintain terminological databases for use in standardization at the following addresses:

- IEC Electropedia: available at http://www.electropedia.org/
- ISO Online browsing platform: available at http://www.iso.org/obp

3.1.1
SOA
semiconductor optical amplifier
optical amplifier in which the active optical waveguide is formed by a semiconductor laser diode structure, which is electrically pumped

Note 1 to entry: SOAs have a similar structure to Fabry-Perot semiconductor laser diodes but with anti-reflection elements at the end surfaces. The optical signal is amplified through the stimulated emission phenomenon in the gain medium.

[SOURCE: IEC 61291-2:2016, 3.1.3, modified – Note 1 to entry has been added.]

3.1.2
SOA chip
semiconductor chip that is the active component of the SOA module

3.1.3
SOA module
fibre-pigtailed optical component that consists of the SOA chip, lenses, optical isolators (if necessary), a thermoelectric cooler (TEC), a thermistor, a package, and optical fibre(s)

3.1.4
population inversion factor
n_{sp}
ratio of the injected carrier density N to the subtraction of the carrier density N_0 where the stimulated emission is equal to the stimulated absorption from N

$$n_{sp} = \frac{N}{N - N_0}$$

Note 1 to entry: In the semiconductor optical amplifier (SOA) field, the population inversion factor is composed of not only carrier density parameters but also combination of the confinement factor Γ, the optical gain g, and internal optical losses α of the optical waveguide of SOA chip. It is defined as:

$$n_{sp} = \frac{N}{N - N_0} \times \frac{\Gamma \times g}{\Gamma \times g - \alpha}$$

Note 2 to entry: The carrier density N_0 at which the stimulated emission is equal to the stimulated absorption is often called "transparent carrier density".

3.2 Abbreviated terms

AR	anti-reflection
ASE	amplified spontaneous emission
BPF	band pass filter
CFP	100 G form factor pluggable
CW	continuous wave
DEMUX	demultiplexer
DFB	distributed feedback
EDFA	erbium-doped fibre amplifier
FWM	four-wave mixing
GbE	gigabit Ethernet
GPON	gigabit capable passive optical network
LD	laser diode
MSA	multi-source agreement
MMI	multi-mode interference
MQWs	multiple quantum wells
NF	noise figure
OA	optical amplifier
OFA	optical fibre amplifier
OLT	optical line termination
ONU	optical network unit

PC	polarization controller
PD	photodiode
PDCE	polarization dependence of coupling efficiency
PDG	polarization dependent gain
PIC	photonic integrated circuit
POL	polarizer
PON	passive optical network
RSOA	reflective semiconductor optical amplifier
SMF	single-mode fibre
SOA	semiconductor optical amplifier
TE	transverse electric
TEC	thermoelectric cooler
TIA	transimpedance amplifier
TM	transverse magnetic
VOA	variable optical attenuator
WDM	wavelength division multiplexing
XGM	cross gain modulation
XPM	cross phase modulation

3.3 Symbols

G	optical gain
I_F	forward current
L	chip length
n_{eff}	effective refractive index
n_{sp}	population inversion factor
PDG_{active}	polarization dependence of active layer gain
PDG_{total}	total polarization dependence of single pass gain
R	reflectivity
ΔG_{ripple}	peak to peak amplitude of gain ripple
$\Delta\lambda_{ripple}$	period of gain ripple
Γ_{TE}	TE mode confinement factor
Γ_{TM}	TM mode confinement factor
λ	wavelength

4 Specific features of SOAs

4.1 SOA chips

Figure 1 shows the schematic diagram of a typical SOA chip. Similar to LDs, SOA chips are less than 1,5 mm in length, 0,5 mm in width, and 0,2 mm in height. Since SOA chips are made of III-V compound semiconductor materials and developed based on the technologies used for laser diodes (LDs), the basic physical mechanisms of generating optical gain in SOA chips are the same as those in LDs. Therefore, the population inversion inside the SOA chip is implemented by a forward current (I_F), and the input optical signals are amplified by the stimulated emission of photons in the active layer of the chip. The cross section of a typical active layer is 1,5 µm in width and 0,1 µm in thickness (height).

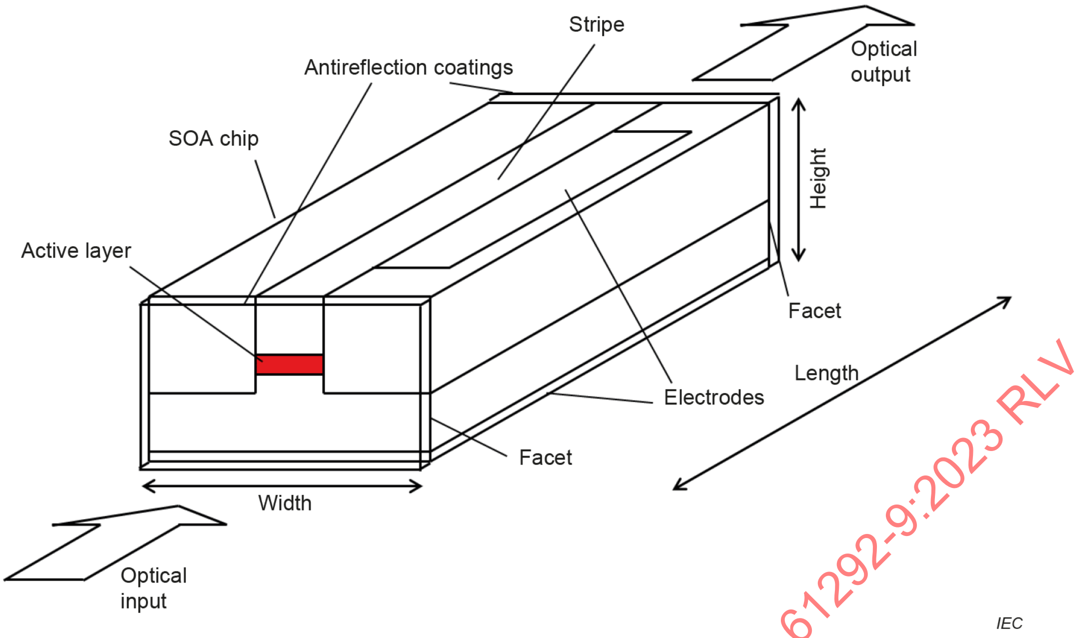


Figure 1 – Schematic diagram of the typical SOA chip

Figure 2 shows an example of the dependency of the SOA gain on the forward current I_F. The current is injected into the chip through electrodes at the top and bottom of the SOA chip, as shown in Figure 1. The gain of the SOA chip can be varied by adjusting the forward current. As shown in Figure 2, by increasing I_F to values greater than 150 mA, typical SOA chips can provide optical gain greater than 20 dB at an input optical power of around –20 dBm.

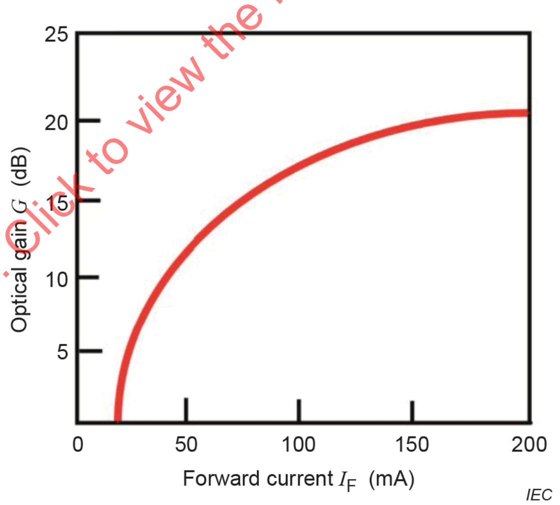
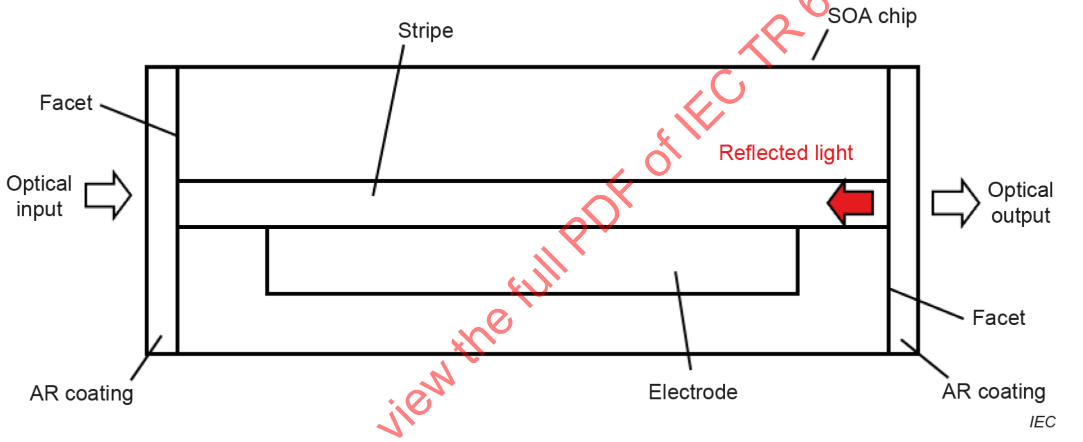
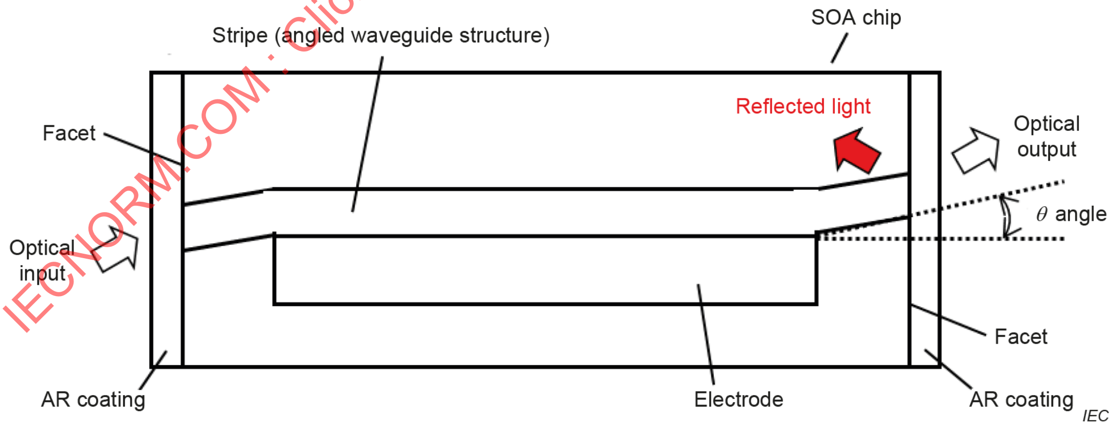


Figure 2 – Example of gain dependency of an SOA chip on forward current

Compared with LDs, the most distinctive feature of SOAs is that the SOA chip has anti-reflection (AR) coatings on both facets to avoid optical feedback between the facets. Since semiconductor materials have a much higher refractive index (> 3 is typical) than air, a facet without anti-reflection coating has a reflectivity of 30 % or above. This feature is suitable for establishing a laser cavity but not for the SOA chip, for which the facet has to have a reflectivity of less than 0,1 % over a wavelength range of greater than 30 nm. To achieve such a low reflectivity, AR coatings are employed on both facets of the SOA chip, as shown in Figure 3. Figure 3 a) and Figure 3 b) show schematic top views of a conventional SOA chip and an SOA chip with an angled waveguide structure, respectively. As shown in Figure 3 a), a conventional SOA chip has a straight stripe, which is normal to the two facets where AR coating is applied. The AR coating consists of a multiple-layer thin film. The thickness (e.g., quarter wavelength) of each film layer is controlled to within ±4 %. The residual reflectivity will cause intra-cavity interference between the facets, which leads to gain ripple or even laser oscillation. When the angle θ between the active stripe layer and the facet is 90°, the reflected light is readily coupled back into the stripe, thus leading to multiple reflections between the facets. One of the best ways to suppress intra-cavity feedback is the introduction of an angled waveguide structure, as shown in Figure 3 b). The reflected light cannot encounter significant multiple reflections when using an angled stripe with θ = 7°. This approach reduces the facet reflectivity to about 0,2 %, and to less than 0,1 % when combined with AR coatings.



a) **Conventional SOA chip**



b) **SOA chip with angled waveguide structure**

Figure 3 – Schematic top view of a typical SOA chip with and without an angled waveguide structure

Another specific feature of SOAs is that the gain wavelength band of SOA chips can be varied by changing the composition of the semiconductor materials using mature LD technologies (i.e., by a band engineering technique). For example, long-wavelength (1 300 nm to 1 600 nm) SOA chips typically use an InGaAsP active layer on an InP substrate, and the peak wavelength of the gain is adjusted by changing the relative concentrations of In, Ga, As and P in the InGaAsP layer. The typical gain wavelength range of SOA chips is greater than 40 nm.

Another specific feature of SOA chips is that they can be integrated with other semiconductor devices, such as tuneable LDs, electro-absorption modulators and passive waveguides, on a single chip. These integrated SOAs are used, for example, as booster amplifiers in tuneable LDs and line amplifiers (loss compensators) in photonic integrated circuits (PICs).

In summary, SOAs have very different physical mechanisms for amplification and, hence, device configuration than conventional optical fibre amplifiers (OFAs).

Figure 4 shows the schematic top view of the SOA module. An SOA chip, a TEC, and optical lenses can be assembled in a butterfly package which has fibre pigtails for the input and output ports. This is the most common package for SOA modules and its size is almost the same as that of 14-pin butterfly LD modules. The use of optical isolators (input and/or output) depends on the application. For example, optical isolators are not employed in SOA modules for bidirectional amplification. The TEC is used to stabilize the temperature of the SOA chip, since more than 100 mA of electric current injected into the SOA chip will cause significant heating inside the chip, which can affect its polarization characteristics. Similar to LD modules, SOA modules are also hermetically sealed with N_2 gas.

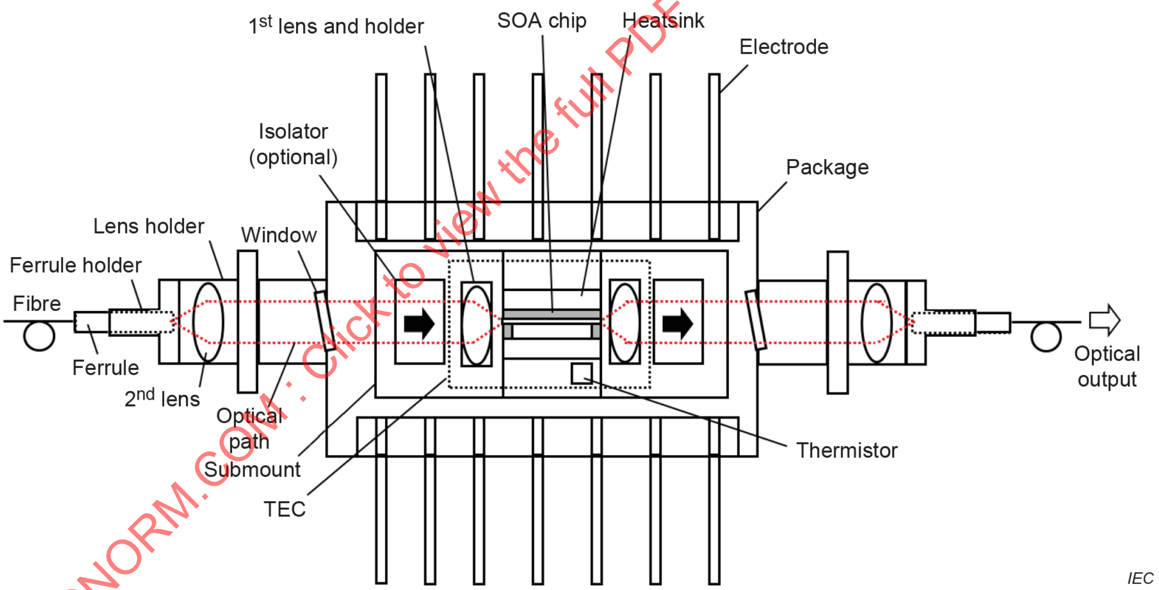


Figure 4 – Schematic top view of a typical SOA module

4.2 Gain ripple

4.2.1 General

Optical feedback inside the SOA chip, resulting from residual reflections at the chip facets, can lead to round-trip resonances when an input optical signal is launched into the chip, as shown in Figure 5.

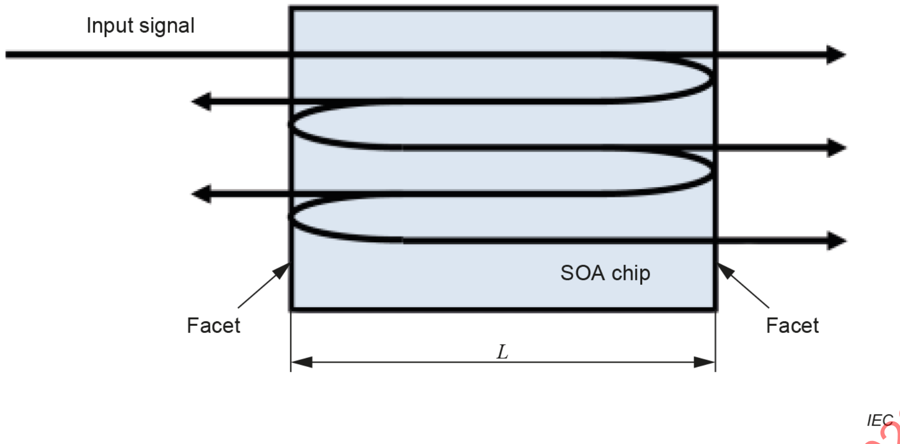


Figure 5 – Schematic diagram of the optical feedback inside the SOA chip

The amplified light from the various round-trip paths can interfere constructively or destructively depending on the wavelength of the signal light. As a result, the SOA gain becomes wavelength dependent, as shown in Figure 6. This gain dependence on wavelength is called gain ripple.

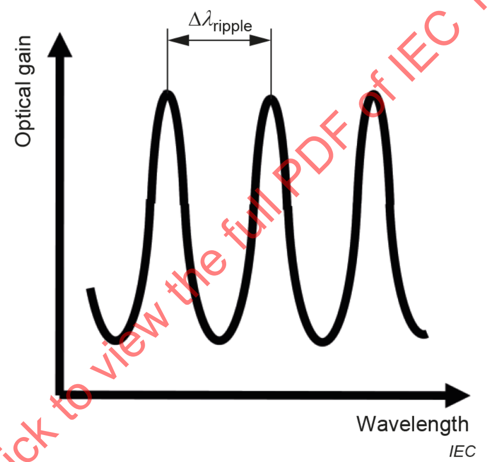


Figure 6 – Schematic diagram of gain ripple

With chip gain G and facet reflectivity R, the peak-to-peak amplitude of the gain ripple ΔG_{ripple} is given by Formula (1).

$$\Delta G_{\text{ripple}} = \frac{(1+G\times R)^2}{(1-G\times R)^2} \qquad (1)$$

At signal wavelength λ, chip length L, and effective refractive index n_{eff}, the period of the gain ripple $\Delta\lambda_{\text{ripple}}$ can be calculated from Formula (2).

$$\Delta\lambda_{\text{ripple}} = \frac{\lambda^2}{2 n_{\text{eff}} L} \qquad (2)$$

At λ = 1 550 nm, for example, $\Delta\lambda_{ripple}$ is approximately 0,29 nm for an SOA chip with n_{eff} = 3,4 and L = 1,2 mm. Since an SOA waveguide typically exhibits birefringence between the transverse electric (TE) and orthogonally polarized transverse magnetic (TM) waves (relative to the chip substrate), $\Delta\lambda_{ripple}$ depends on the polarization state of the input light.

4.2.2 Theoretical calculation of gain ripple

4.2.2.1 SOA gain and gain ripple

Figure 7 shows the simplified model of a Fabry-Perot type SOA, which represents a typical SOA structure of length L and power reflectivities R_1 and R_2, respectively.

Assuming a uniform gain profile, the output electric field E_{out} in the presence of multiple reflections in the SOA cavity is given by Formula (3).

$$\begin{aligned} E_{out} &= \sqrt{(1-R_1)(1-R_2)G_s}\, E_{in} \exp(-j\beta_z L) \\ &\times\left[1+\sqrt{R_1R_2}\, G_s \exp(-2j\beta_z L) + R_1R_2\, G_s^2 \exp(-4j\beta_z L)+\cdots\right] \\ &= \frac{\sqrt{(1-R_1)(1-R_2)G_s}\, E_{in} \exp(-j\beta_z L)}{1-\sqrt{R_1R_2}\, G_s \exp(-2j\beta_z L)} \end{aligned} \qquad (3)$$

where

E_{in} is the amplitude of the input optical signal (E_{input} in Figure 1);

G_s is the single pass power gain;

β_z is the (longitudinal) propagation constant of the field in the cavity.

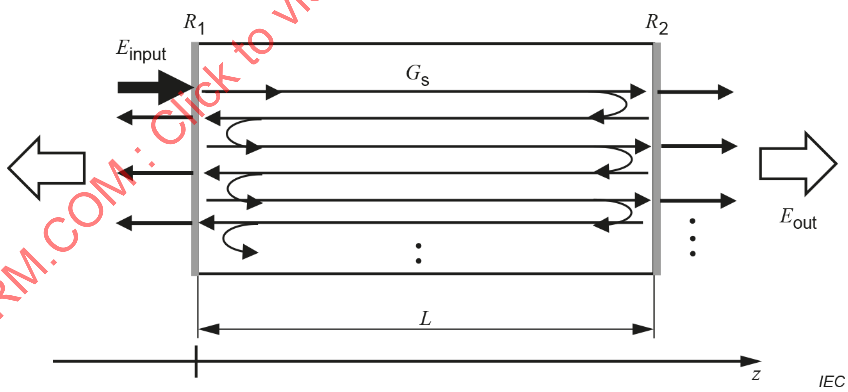


Figure 7 – Illustrated model of a Fabry-Perot type SOA

Then the overall SOA gain G is given by Formula (4).

$$G = \left|\frac{E_{out}}{E_{input}}\right|^2 = \frac{(1-R_1)(1-R_2)G_s}{\left(1-G_s\sqrt{R_1R_2}\right)^2 + 4G_s\sqrt{R_1R_2}\sin^2(\beta_z L)} \qquad (4)$$

Depending on the value of $\beta_z L$, the SOA gain G calculated from Formula (4) varies between maximum and minimum values. When $\sin^2(\beta_z L)$ is zero in Formula (4), the wavelength of the input signal is equal to a multiple of the cavity resonance frequency, and G assumes its maximum value G_{max}, which is given by Formula (5).

$$G_{max} = \frac{(1-R_1)(1-R_2)G_s}{\left(1-G_s\sqrt{R_1 R_2}\right)^2} \tag{5}$$

In contrast, G is minimum when $\sin^2(\beta_z L)$ is equal to 1, which represents a phase mismatch of π between the input signal and the cavity resonance frequency. The minimum gain G_{min} is given by Formula (6).

$$G_{min} = \frac{(1-R_1)(1-R_2)G_s}{\left(1+G_s\sqrt{R_1 R_2}\right)^2} \tag{6}$$

The gain ripple ΔG_{ripple} is defined as the ratio of G_{max} to G_{min}, which can be readily calculated from Formulae (5) and (6), as shown in Formula (7).

$$\Delta G_{ripple} = \frac{G_{max}}{G_{min}} = \frac{\left(1+G_s\sqrt{R_1 R_2}\right)^2}{\left(1-G_s\sqrt{R_1 R_2}\right)^2} \tag{7}$$

4.2.2.2 SOA gain ripple derivation from ASE spectrum measurement

If there is no optical input signal, the output of an SOA is ASE light only. Figure 8 illustrates this situation for the same Fabry-Perot structure as shown in Figure 1, having length L, power reflectivities R_1 and R_2, and single pass power gain G_s. The only difference to Figure 1 is the absence of an optical input signal.

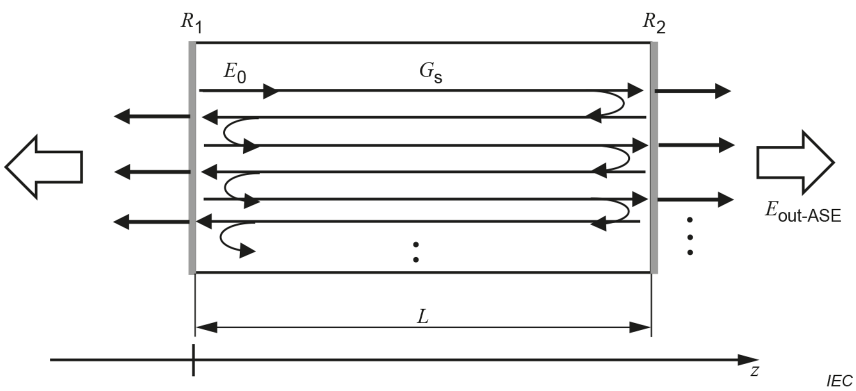


Figure 8 – Illustrated model of ASE output from an SOA

Similar to the case discussed in 4.2.2.1, the output electric field of the ASE, $E_{\text{out-ASE}}$, is impacted by multiple reflections in the SOA cavity. This can be calculated by assuming a uniform gain profile.

Letting E_0 denote the amplitude of the initial ASE electric field, the ASE output field $E_{\text{out-ASE}}$ is given by Formula (8).

$$\begin{aligned} E_{\text{out-ASE}} &= \sqrt{(1-R_2)G_s}\, E_0 \exp(-j\beta_z L) \\ &\times\left[1+\sqrt{R_1R_2}\, G_s \exp(-2j\beta_z L) + R_1R_2\, G_s^2 \exp(-4j\beta_z L)+\cdots\right] \\ &= \frac{\sqrt{(1-R_2)G_s}\, E_0 \exp(-j\beta_z L)}{1-\sqrt{R_1R_2}\, G_s \exp(-2j\beta_z L)} \end{aligned} \quad (8)$$

Then the ASE output power is given by Formula (9).

$$\left|E_{\text{out-ASE}}\right|^2 = \frac{(1-R_2)G_s E_0^2}{\left(1-\sqrt{R_1R_2}\, G_s\right)^2 + 4\sqrt{R_1R_2}\, G_s \sin^2(\beta_z L)} \quad (9)$$

Moreover, the ASE gain G_{ASE} is given by Formula (10).

$$G_{\text{ASE}} = \left|\frac{E_{\text{out-ASE}}}{E_0}\right|^2 = \frac{(1-R_2)G_s}{\left(1-G_s\sqrt{R_1R_2}\right)^2 + 4G_s\sqrt{R_1R_2}\sin^2(\beta_z L)} \quad (10)$$

Similar to the SOA signal gain G, discussed in 4.2.2.1, the ASE gain G_{ASE} in Formula (10) varies between a maximum value $G_{\text{ASE-max}}$ and a minimum value $G_{\text{ASE-min}}$, depending on the value of $\beta_z L$. $G_{\text{ASE-max}}$ and $G_{\text{ASE-min}}$ are given by Formulae (11) and (12).

$$G_{\text{ASE-max}} = \frac{(1-R_2)G_s}{\left(1-G_s\sqrt{R_1R_2}\right)^2} \quad (11)$$

$$G_{\text{ASE-min}} = \frac{(1-R_2)G_s}{\left(1+G_s\sqrt{R_1R_2}\right)^2} \quad (12)$$

Hence, the ripple $\Delta G_{\text{ripple-ASE}}$ observed in the ASE gain is given by Formula (13).