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REDLINE VERSION

TECHNICAL REPORT

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

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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- withdrawn,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).

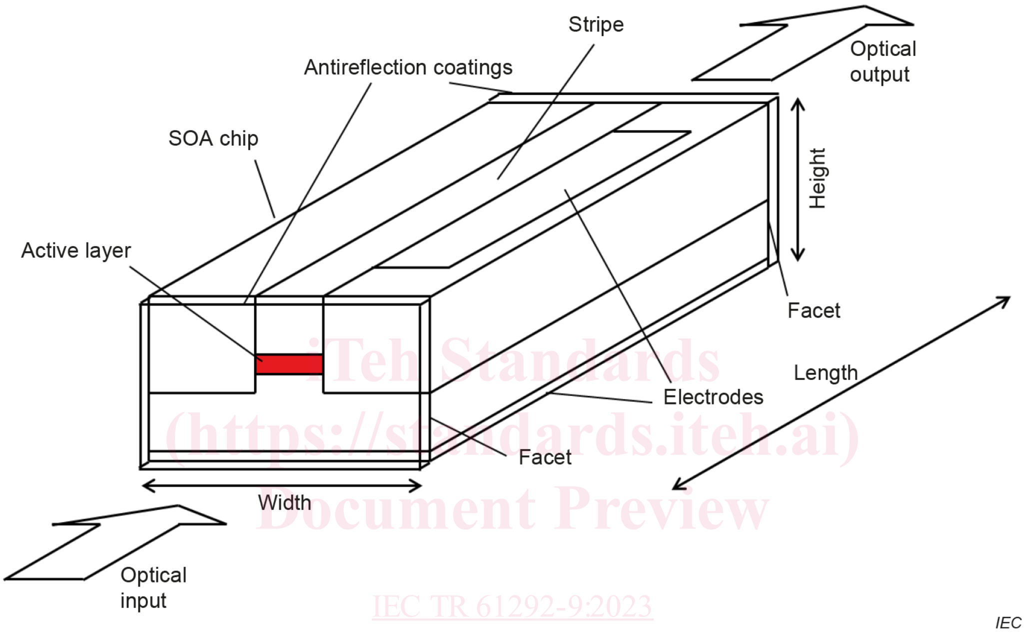

Figure 1 – Schematic diagram of the typical SOA chip

~~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.

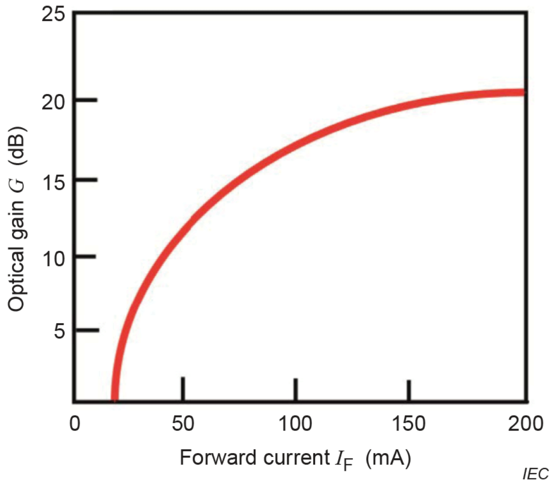

Figure 2 – Example of gain dependency of an SOA chip on forward current

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 θ = 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.

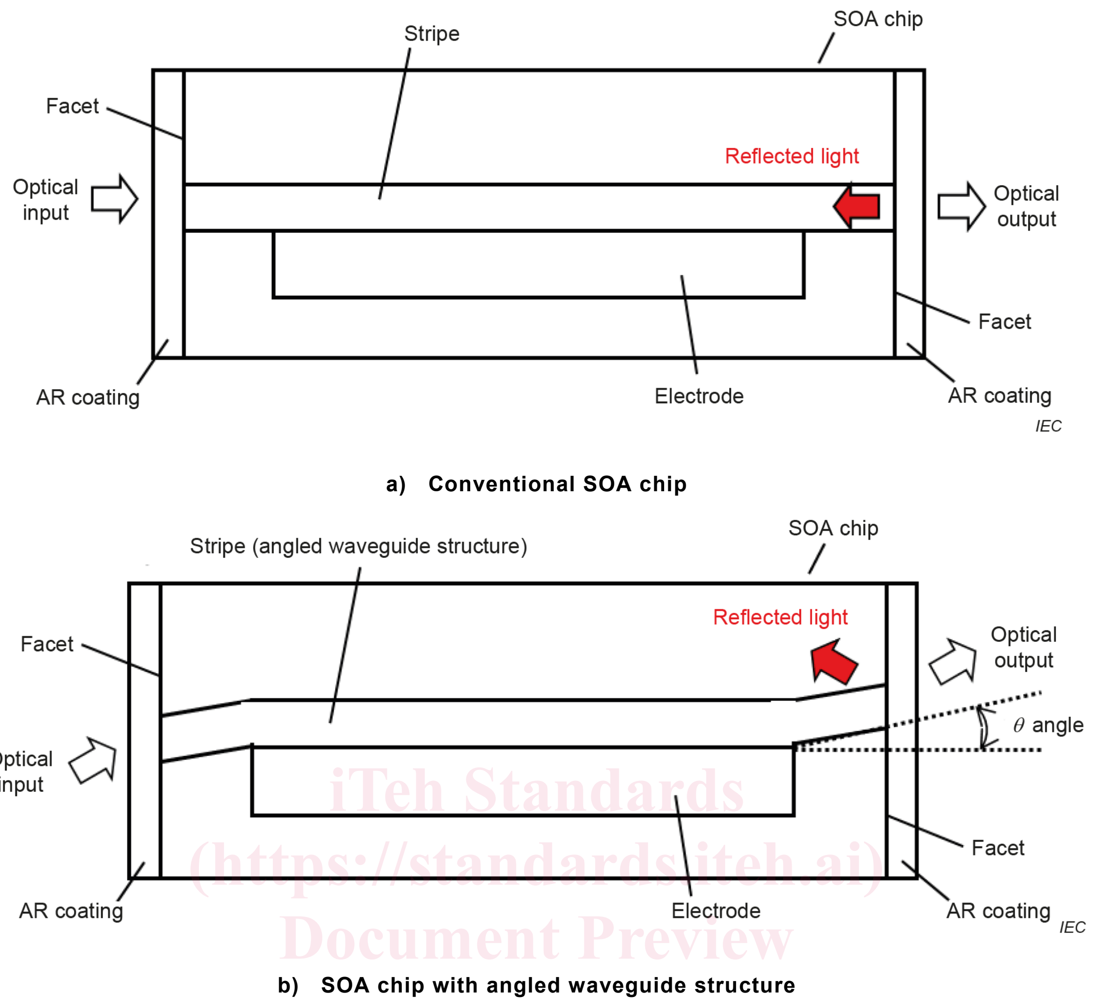

Figure 3 – Schematic top view of a typical SOA chip with and without an angled waveguide structure

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