REF-001008, Rev 3

PIC Application Note
SOA Model and Usage

11-08-2022

Contents

1. Revision History

Rev	Date	Revised by	Comments
1.0	10/20/2022	H. Zhao	Initial draft
2.0	11/02/2022	H. Zhao	Updated model validation and appendix
2.1	11/03/2022	S. McGowan	Update for new OpenLight document release number
3.0	11/08/2022	H. Zhao	Normalized Eq.5 and Eq.6, added test dataset description, updated document title.

2. List of Figures

3. References

[1] L. Coldren, S. Q. Corzine, M. L. Mashanovitch, Diode lasers and photonic integrated circuits, John Wiley& Sons, Hoboken, 2nd ed, 2011.

[2] Y. Said, H. Rezig and A. Bouallegue, Analysis and noise effects in long semiconductor optical amplifier, The Open Optics Journal, 2, pp. 61-66, 2008.

[3] https://mathworld.wolfram.com/NewtonsMethod.html.

4. Glossary

O-to-O Optical-to-Optical

SOA Semiconductor Optical Amplifier

PIN Diode structure P(doped) -Intrinsic -N(doped)

SOI Silicon on Insulator

SiPh Silicon Photonics

RSM Response Surface Method

FWHM Full Width at Half Maximum

NF Noise Figure

ASE Amplified Spontaneous Emission

5. Document Scope

This Application Note provides operation conditions for OpenLight Semiconductor Optical Amplifier (SOA) and detailed models for the SOA's gain and noise figure (NF) performance.

6. Introduction

Semiconductor optical amplifiers (SOAs) are O-to-O components to amplify optical signal through group III-V gain materials. In contrast to semiconductor lasers, SOAs have no optical feedback and thus amplify the light in a single pass. The OpenLight SOA has a PIN diode waveguide structure on a hybrid SiPh platform. The III-V active material is heterogeneously bonded onto Silicon on Insulator (SOI) substrates. Light is guided in and out of the SOA vias evanescent coupling by the Si waveguides. Transition tapers between SOA and Si waveguide are placed on both sides of the III-V active region.

The OpenLight SOA described in this Application Note is designed for O-band operation. The width of the SOA is 2 μm (W = 2 μm). The length of its active region length (L) can vary in the range between 40 μm and 440 μm, depending on the gain requirement.

7. SOA Model

Schematic of the SOA structure is demonstrated in Fig. 1. A III-V gain epi is shown on the top, which is heterogeneously bonded onto the SOI waveguide. The SOI waveguide consists of three sections: input taper, straight SOA waveguide and output taper. The length of the straight SOA waveguide is L (μm). The length of gain epi (L_t) is the same as the total lengths of the whole SOI waveguide underneath. The length of the tapers on both sides are 460 μm in total.

$$L_t = L + L_{input\ taper} + L_{output\ taper} = L + 460\ [\mu m] \quad \text{(Eq.1)}$$

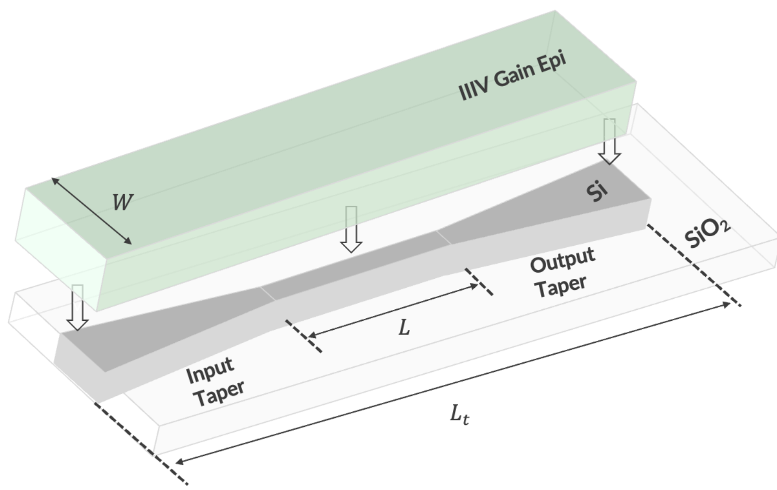

Figure 1. Schematic of the SOA design.

With the drive current (I), the current density (J) inside the SOA is given by:

$$J = \frac{I}{W \times L_t} \quad \text{(Eq.2)}$$

where W is the width of the gain ridge waveguide. In our current sample device layout, SOA has a nominal length of $L = 240\ \mu\text{m}$ (L_t = 700 μm). In this Application Note, the model is parameterized over SOA length (L) from $40\ \mu\text{m}$ to $440\ \mu\text{m}$ over operation temperature (T) range from 0°C to 100°C. Gain and noise figure model are experimentally validated from 35°C to 80 °C. Validation across the full temperature range will be added in an upcoming document revision.

7.1. Unsaturated Gain

Optical signal launched into an SOA is amplified through stimulated emission. Optical gain (g) is defined as the ratio of output optical power (P_o) existing an SOA with respect to the input optical power (P_{in}).

$$g = \frac{P_o}{P_{in}} \quad \text{(Eq.3)}$$

Gain (g) is an unitless characteristics, and often expressed in decibel format.

$$g_{dB} = 10\ \mathrm{Log}_{10}[g] \qquad \text{(Eq.4)}$$

The gain spectrum of an SOA depends on the material properties and the operation conditions: temperature (T), driving current density (J) and input power level (P_{in}). When input power level is low, SOA operates in its unsaturated regime, with a linear gain defined as unsaturated gain (g_0), following Lorentzian function line shape:

$$f = \frac{FWHM}{(\lambda pk - \lambda)^2 + \left(\frac{FWHM}{2}\right)^2} \qquad \text{(Eq.5)}$$

$$g_0 = \frac{f \times 10^{0.1 \times g_{pk}}}{max\ (f)} = \frac{f \times 10^{0.1 \times g_{pk}}}{4/FWHM} \quad \text{[linear unitless]} \qquad \text{(Eq.6)}$$

where g_{pk} is the peak gain [dB], λ_{pk} is the wavelength [nm] where peak gain is achieved, FWHM is the full width at half maximum of the gain spectrum [nm], as shown in Fig. 2.

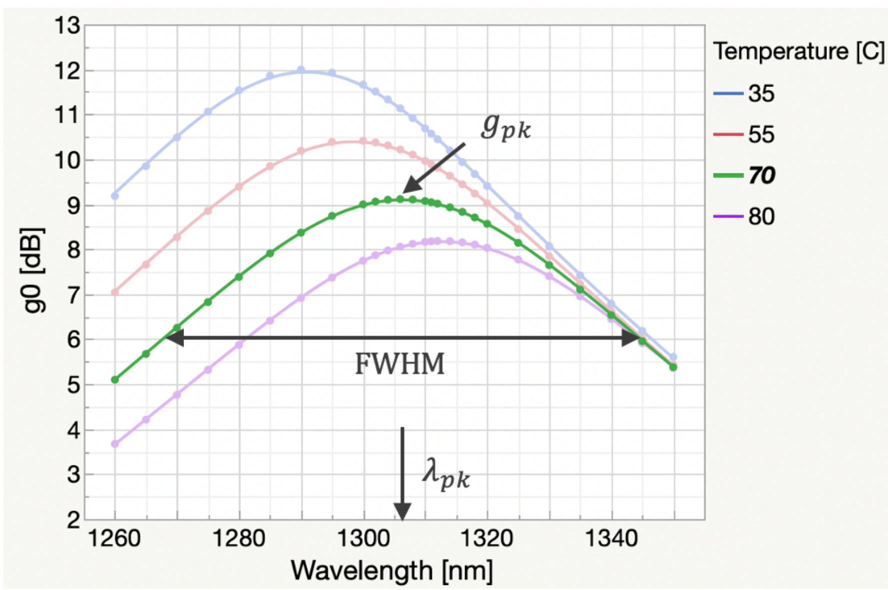

Figure 2. Unsaturated gain spectrum of SOA.

Unsaturated SOA gain of various active lengths were measured with increasing driving current density and temperature from 35 °C to 80 °C. There are 13 devices selected across each 8-in wafer and 3 wafers were tested. We fit the analytical expression for Eq.5 and Eq.6 to extract fits for the model input parameters g_{pk}, λ_{pk}, and FWHM. A compact model based on response surface method (RSM) is given below:

T: [35, 80] °C

J: [3, 7] kA/cm^2

L: [40, 440] μm

$$
\begin{aligned}
g_{pk}(\mathrm{T,J,L})\ [\mathrm{dB}] = {} & 4.678 - 0.0729 * \mathrm{T} + 10.098 * \mathrm{Ln(J)} - 0.001380 * (\mathrm{L}+460) \\
& - 0.00024 * (\mathrm{T} - 60) * (\mathrm{T} - 60) - 0.0081 * \mathrm{Ln(J)} * (\mathrm{T} - 60) - 2.158 * \mathrm{Ln(J)} * \mathrm{Ln(J)} \\
& - 0.0001589 * (\mathrm{T} - 60) * (\mathrm{L} - 240) + 0.02311 * \mathrm{Ln(J)} * (\mathrm{L} - 240) \\
& - 0.000001886 * (\mathrm{T} - 60) * (\mathrm{T} - 60) * (\mathrm{L} - 240) \\
& - 0.00002088 * \mathrm{Ln(J)} * (\mathrm{T} - 60) * (\mathrm{L} - 240) \\
& - 0.005336 * \mathrm{Ln(J)} * \mathrm{Ln(J)} * (\mathrm{L} - 240)
\end{aligned}
\quad \text{(Eq.7)}
$$

$$
\begin{aligned}
\lambda_{pk}(\mathrm{T,J,L})\ [\mathrm{nm}] = {} & 1273.73 + 0.6817 * \mathrm{T} - 28.73 * \mathrm{Ln(J)} + 0.01362 * (\mathrm{L} + 460) \\
& + 0.004585 * (\mathrm{T} - 60) * (\mathrm{T} - 60) - 0.1076 * \mathrm{Ln(J)} * (\mathrm{T} - 60) + 8.787 * \mathrm{Ln(J)} * \mathrm{Ln(J)} \\
& + 0.00004185 * (\mathrm{T} - 60) * (\mathrm{L} - 240) - 0.02367 * \mathrm{Ln(J)} * (\mathrm{L} - 240) \\
& - 0.0000002230 * (\mathrm{T} - 60) * (\mathrm{T} - 60) * (\mathrm{L} - 240) \\
& + 0.000136 * \mathrm{Ln(J)} * (\mathrm{T} - 60) * (\mathrm{L} - 240) + 0.004894 * \mathrm{Ln(J)} * \mathrm{Ln(J)} * (\mathrm{L} - 240)
\end{aligned}
\quad \text{(Eq.8)}
$$

$$
\begin{aligned}
\mathrm{FWHM}(\mathrm{T,J,L})\ [\mathrm{nm}] = {} & 120.15 - 0.08555 * \mathrm{T} + 0.3837 * \mathrm{Ln(J)} - 0.07255 * (\mathrm{L} + 460) \\
& + 0.00007784 * (\mathrm{T} - 60) * (\mathrm{T} - 60) + 0.2386 * \mathrm{Ln(J)} * (\mathrm{T} - 60) + 2.759 * \mathrm{Ln(J)} * \mathrm{Ln(J)} \\
& - 0.0004342 * (\mathrm{T} - 60) * (\mathrm{L} - 240) + 0.003947 * \mathrm{Ln(J)} * (\mathrm{L} - 240) \\
& + 0.00002085 * (\mathrm{T} - 60) * (\mathrm{T} - 60) * (\mathrm{L} - 240) \\
& + 0.000009466 * \mathrm{Ln(J)} * (\mathrm{T} - 60) * (\mathrm{L} - 240) \\
& - 0.0007991 * \mathrm{Ln(J)} * \mathrm{Ln(J)} * (\mathrm{L} - 240)
\end{aligned}
\quad \text{(Eq.9)}
$$

Based on the model, the typical values of the unsaturated gain at 80 °C for the nominal SOA design (W = 2 μm, L = 240 μm) are listed in Table 1.

Table 1. Unsaturated gain [dB] for the nominal SOA design (W = 2 μm, L = 240 μm) at 80°C.

	J = 3 kA/cm^2	J = 5 kA/cm^2	J = 7 kA/cm^2
λ =1304 nm	5.6	8.0	8.8
λ =1311 nm	6.0	8.2	9.0
λ =1318 nm	6.1	8.1	8.9

To validate the compact model, we compared the model for the nominal SOA design with measured results, shown in Fig. 3. The blue dot/line in Fig.3 is the measured gain median. The model matches well with the measured median for wavelength ranging from 1280 nm to 1320 nm, especially at higher temperature (70 °C and 80 °C). At 35 °C, the deviation is more noticeable at longer wavelength (λ > 1340 nm).

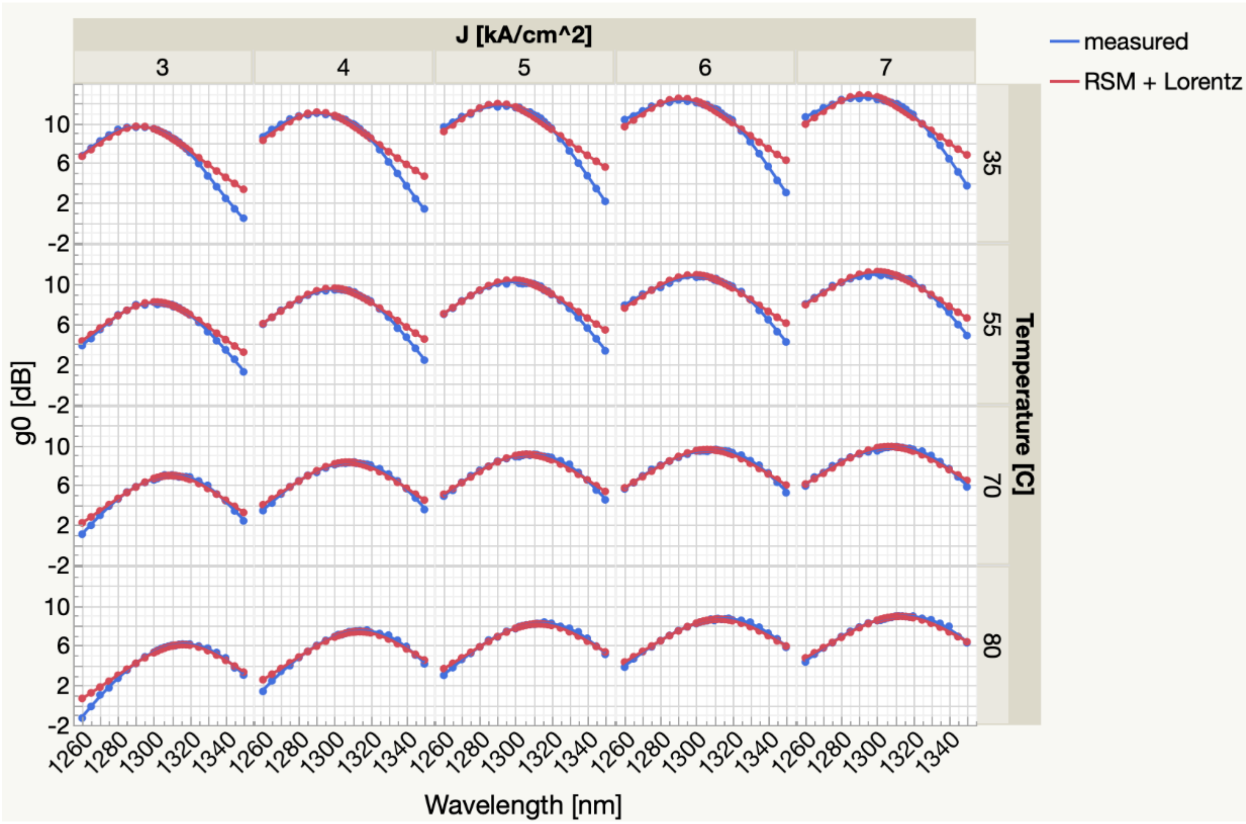

Figure 3. Unsaturated gain model compared to the measurements.

7.2. Gain Saturation

When the input power (and output power) of SOA increases to a relatively large level, carriers in the active region are depleted, which causes the net gain decrease and saturate. Deriving from the carrier rate equation, SOA gain is given by:

$$g = g_0 \exp\left[-\frac{g-1}{g}\frac{P_o}{P_s}\right] \quad \text{[linear unitless]} \qquad \text{(Eq.10)}$$

$$P_s = \frac{Wdh\nu}{a\Gamma\tau} \quad \text{[linear unitless]} \qquad \text{(Eq.11)}$$

where g_0 is the unsaturated gain when $P_o \ll P_s$, W and d are the width and thickness of the active layer, a is the differential gain of the materials, Γ is the confinement factor, τ is the carrier lifetime, h is the Planck constant and ν is the optical frequency.

Output Saturation power, P_{os}, is defined when the gain decreases to half of g_0,

$$P_{os} = \frac{g_o \ln 2}{g_o - 2} P_s \quad \text{[linear unitless]} \qquad \text{(Eq.12)}$$

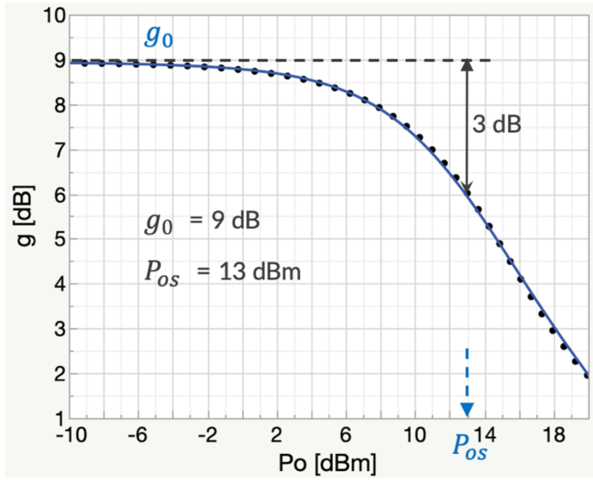

Figure 4. SOA gain as a function of output power.

Figure 4 shows an example of gain profile as a function of output optical power and how to obtain g_0 and P_{os} from the gain characterization. With extracted g_0 and P_{os}, gain is obtained by numerically solving Eq.10 (see Appendix for details). Gain calculated by Eq.10 is compared with the measurement results, as shown in Fig. 5. From low output power (unsaturated region) to P_{os}, it matches well with the experimental results while deviation is increased for $P_{\mathrm{o}} > P_{os}$.

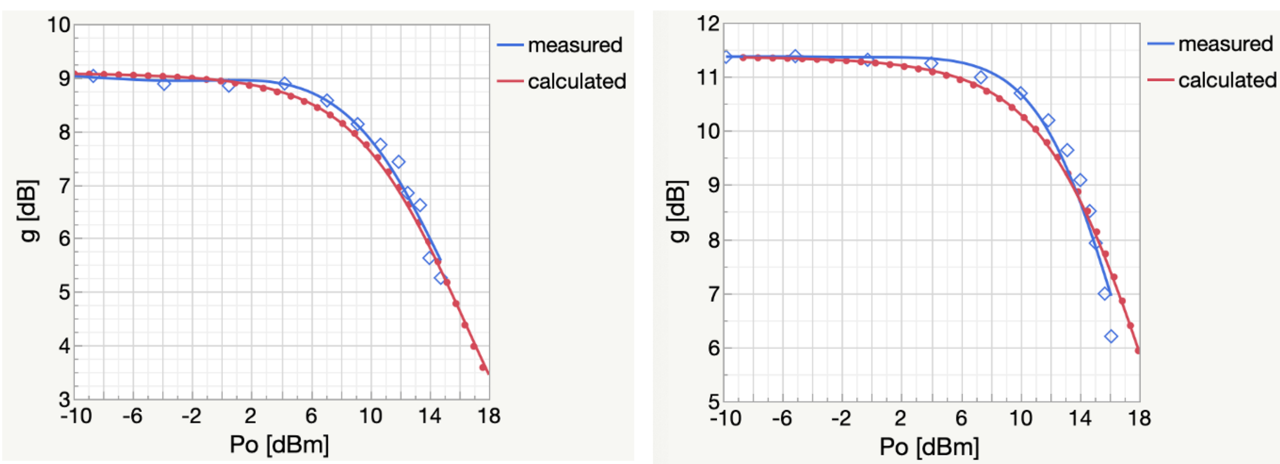

Figure 5. Measured and calculated gain as a function of output power.

Therefore, to solve saturated gain as a function of output power, we will need both g_0 and P_{os}. Firstly, as described in Section 7.1, we can get g_0 from Eq.5 - Eq.9. Secondly, to model P_{os}, 13 devices across an 8-in wafer were measured with increasing input optical power. Then we extracted the output saturation power $P_{os} = P_{os}\ (\lambda, J, T)$ and built a model via response surface method (RSM) with three input parameters: λ [nm], J [kA/cm^2], T[°C] (see Eq. 13).

As shown in Fig.6, RSM based P_{os} aligns with the measured median. The maximum error is only 0.4 dB, which happened at 1318 nm (80 °C) under 7 kA/cm^2. To note that we have experimentally validated the output saturation power only from 1304 nm to 1318 nm due to insufficient dataset out of this range. Saturated power across the full O band (1260nm – 1360nm) will be added in an upcoming document revision.

λ: [1304, 1318] nm

J: [3, 7] kA/cm^2

T: [35, 80] °C

P_{os} (λ, J, T) [dBm]= -74.08+ 0.06226*λ - 0.008877*T + 0.994*J +

-0.08721*(J - 4.571)* (J - 4.571) + 0.01752*(λ - 1310.8)* (λ - 1310.8)

-0.00002341*(T - 60.07)*(T - 60.07) - 0.001266*(λ - 1310.8)*(T- 60.07)

-0.001763* (T - 60.07)*(J- 4.571) - 0.008584*(λ - 1310.8)*(J- 4.571)

(Eq.13)

Output saturation power for the nominal SOA design (W = 2 μm, L = 240 μm) at fixed current density of J = 7 kA/cm^2 are summarized in Table 2, for three temperatures.

Table 2: P_{os} [dBm] for the nominal SOA design (W = 2 μm, L = 240 μm) at J = 7 kA/cm^2.

	T = 35 °C	T = 55 °C	T = 80 °C
λ = 1304	14.1	14.0	13.9
λ = 1311	13.8	13.5	13.2
λ = 1318	15.2	14.8	14.2

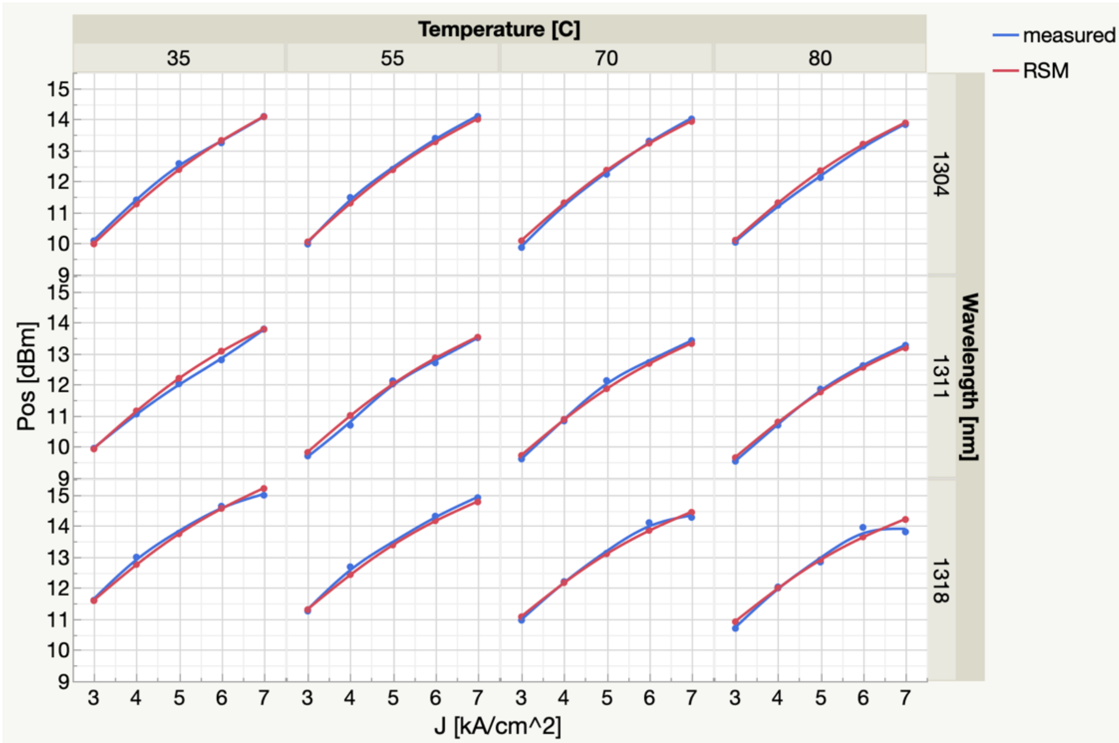

Figure 6. Output saturation power model compared to the measurements.

7.3. Noise Figure

The major contribution to the noise generated in SOA is the amplified spontaneous emission (ASE) noise. To quantify the impact of noises on output signal, noise figure (NF) is defined as the ratio between the optical signal to noise ratio of the signal at the input and output of the SOA.

$$NF = \frac{(S/N)_{in}}{(S/N)_{out}} = \frac{2S_{ASE}}{h\nu g_0} + \frac{1}{g_0} \quad \text{(Eq.14)}$$

where h is the Planck constant, ν is the optical frequency, g_0 is SOA unsaturated gain, S_{ASE} is ASE power spectrum density. Noise figure for 39 devices from 3 wafers at different bias currents and temperatures were measured and the response surface model is shown below.

λ [1260, 1350] nm

J: [3, 7] kA/cm^2

T: [35, 80] °C

. NF (λ, J, T) [dB] = 131.58 + -0.09959*λ + 0.08972*T -5.0895*Ln(J)

+ 2.7334*Ln(J)*Ln(J) + 0.0009195 *(λ - 1306.38)* (λ - 1306.38)

+ 0.0007484*(T - 60)*(T - 60) -0.001299*(λ - 1306.38)*(T - 60)

$- 0.07995*(T - 60)*Ln(J) + 0.103*(\lambda-1306.38)*Ln(J)$

$+ 0.0005740*(\lambda - 1306.38)*(T - 60)*Ln(J)$

$+ 0.0197*Ln(J)*Ln(J)*(T - 60) - 0.02785*Ln(J)*Ln(J)*(\lambda - 1306.38)$

$-0.0003141*(T - 60)*(T - 60)*Ln(J) -0.00001095*(T - 60)*(T - 60)*(\lambda - 1306.38)$

$-0.0002678*(\lambda - 1306.38)*(\lambda-1306.38)*Ln(J)$

$+ 0.000003281*(\lambda-1306.38)*(\lambda - 1306.38)*(T - 60)$

$-0.4606*Ln(J)*Ln(J)*Ln(J) - 0.000002634*(\lambda - 1306.38)*(\lambda - 1306.38)*(\lambda - 1306.38)$

(Eq.15)

Table 3: NF [dB] for the nominal SOA design (W = 2 μm, L = 240 μm) at J = 7 kA/cm^2

	T = 35 °C	T = 55 °C	T = 80 °C
λ = 1304	3.8	3.9	4.2
λ = 1311	3.8	3.9	4.1
λ = 1318	3.7	3.9	4.1

Noise figure for the nominal SOA design (W = 2 μm, L = 240 μm) operated at J = 7 kA/cm^2 is shown in Table 3. Please note that this model is validated only under the unsaturated operation region ($P_o \ll P_s$). Figure 7 plots the measured NF median and the built RSM model, which show very good matching.

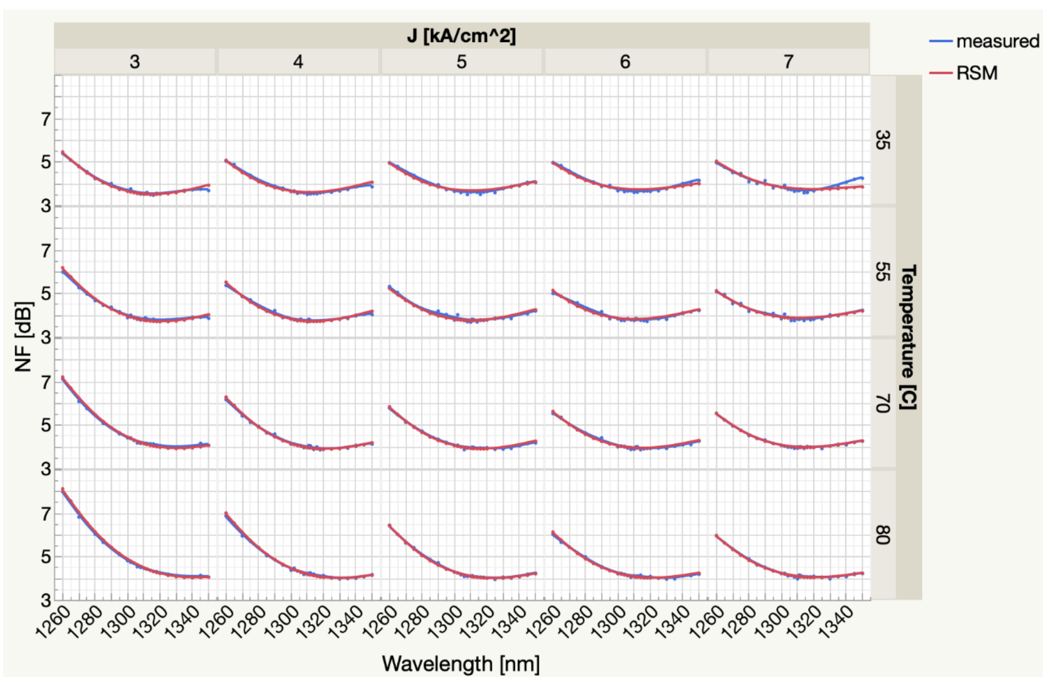

Figure 7. Noise figure model compared to the measurements.

8. Appendix

Newton iteration is also known as Newton-Raphson method. It solves equation $f(x) = 0$ by starting with an arbitrary initial trial point (x_0) and then sorts the solution (x_n) iteratively until $f(x_n) \approx 0$. x_n is given by:

$$x_n = x_{n-1} - \frac{f(x_{n-1})}{f'(x_{n-1})}$$

Where $n = 1, 2, 3, \dots \dots$ In Section 7.2, the saturation gain is given by:

$$g = g_0 \exp\left[-\frac{g-1}{g}\frac{P_o}{P_S}\right]$$

Since $P_o = gP_{in}$, saturation gain can also be written as:

$$g = g_0 \exp\left[(1-g)\frac{P_{in}}{P_S}\right]$$

Solving the saturation gain equals to find the solution for $f(x) = 0$ and the first derivative term is also given below:

$$f(x) = x - g_0 \exp\left[(1-x)\frac{P_{in}}{P_S}\right]$$

$$f'(x) = 1 + g_0\frac{P_{in}}{P_S}\exp\left[(1-x)\frac{P_{in}}{P_S}\right]$$

The solution can be implemented in Python as:

```
def Newton iteration (Pos, g0, Pin):
    epsilon_1 = 1e-5
    epsilon_2 = 1e-4
    Ps = Pos*(g0-2)/g0/log(2)
    x = 2
    c1 = 1
    c2 = 1
    while (c1>epsilon_1 or c2>epsilon_2 ):
        f = x - g0*exp(Pin*(1-x)/Ps)
        f1 = 1 + g0*Pin*exp(Pin*(1-x)/Ps)/Ps
        x1 = x - f/f1
        c1 = abs(f)
        c2 = abs(x1 - x)
        x = x1
    return x
```