Wideband Steady-State Numerical Model of a Tensile-Strained Bulk SOA

Michael J. Connelly

Optical Communications Research Group
Department of Electronic and Computer Engineering
University of Limerick
Ireland

UNIVERSITY of LIMERICK
OLLSCOIL LUIMNIGH

sfi
science foundation ireland
fondúireacht eolaíochta éireann

Outline

1. Introduction
2. Steady-state model
3. Numerical algorithm
4. Simulations
5. Conclusion

Introduction

SOA technology shows great promise for use in optical communication networks.

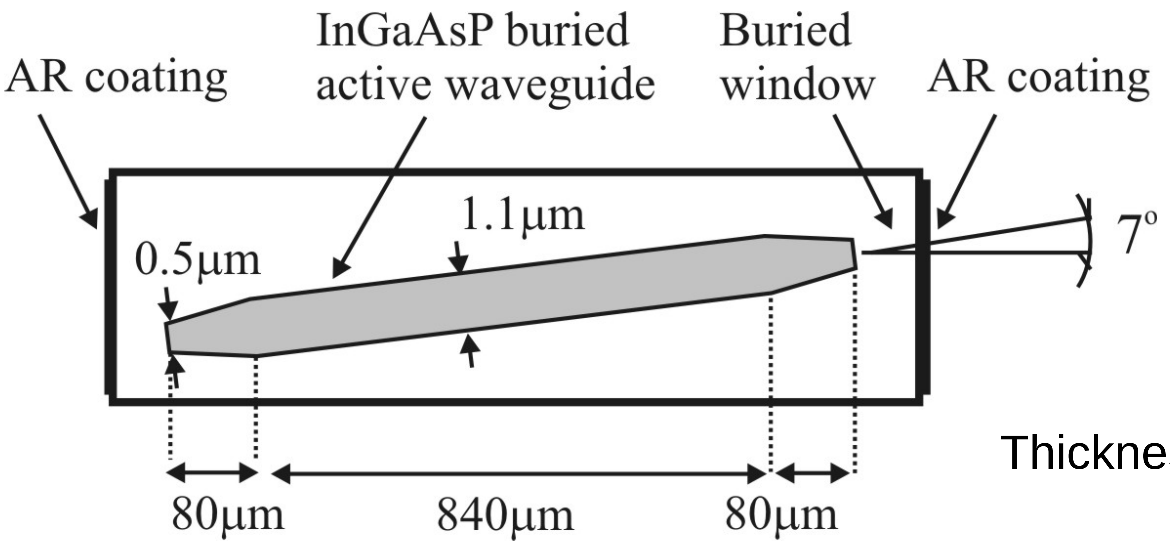
Analytical or numerical models are required to aid device design and predict operational characteristics.

SOAs can be used to amplify signals at different wavelengths – need a wideband SOA model.

Previously developed a wideband steady-state numerical model of an unstrained bulk SOA with a square cross-section active waveguide*.

*M. Connelly, ''Wideband semiconductor optical amplifier….., ' *IEEE J. Quantum Electron*, 2001

- We extend the model to a commercial tensile-strained bulk SOA, with a rectangular cross-section active waveguide, manufactured by Kamelian.



Thickness = 0.1 μm

SOA – top view of the active waveguide

Device geometry and some material parameters supplied by Amphotonics.

Steady-state model

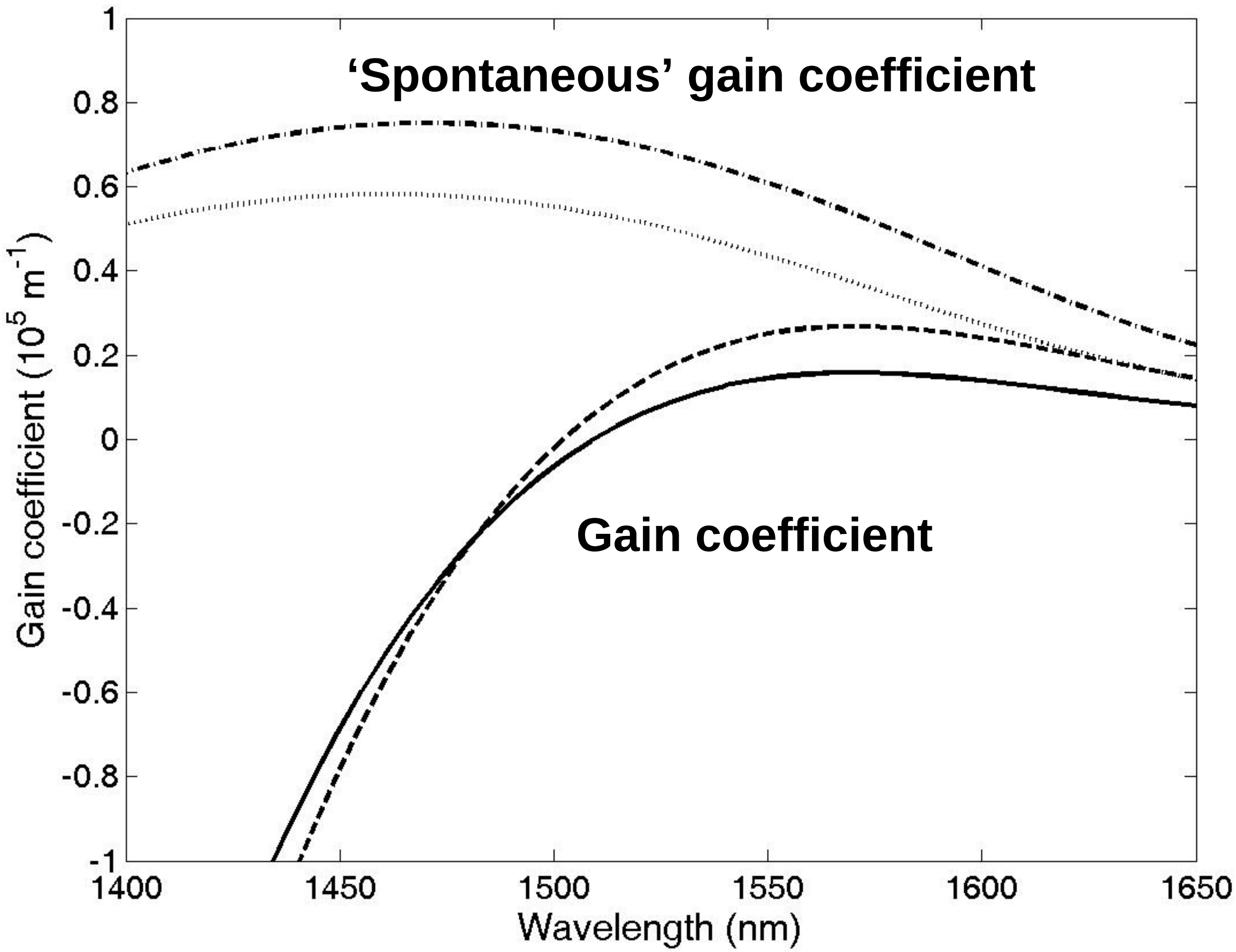
- Active material valence Band structure and matrix elements determined using 6x6 Hamiltonian, which includes the split-off band *.
- Polarisation dependent material gain coefficient

$$g_{m,p}(\hbar\omega)=\frac{C_g}{\hbar\omega}\sum_{b=LH,HH,SO}\int_0^{\infty}\int_0^{\pi}k^2\sin\theta\left|M_{p,b}(k,\theta)\right|^2 L_z\left[E_{cv,b}(k,\theta)\right]\left[f_c(k)+f_{v,b}(k,\theta)-1\right]d\theta\,dk$$

Sech lineshape function $$L_z(E_{cv})=\frac{\tau_r}{\hbar\pi}\operatorname{sech}\left[\frac{\tau_r}{\hbar}(E_{cv}-\hbar\omega)\right]$$

The radiative recombination rate is determined in a similar manner.

* Jones G. and E.P. O'Reilly. *IEEE J. Quantum Electron.*, 1993.



Typical polarisation dependent material gain and ‘spontaneous’ gain coefficient spectra.
Carrier density = 3 x 10^{24} m^{-3}

The model is based on a set of coupled differential equations that describe the interaction between the carrier density and the signal and ASE photon rates.

It is assumed that transverse variations in the carrier density and photon rates are negligible and that the SOA has negligible facet reflectivities.

Travelling-wave equation for the forward propagating signal intensity (photons/s)

$$\frac{d\left|E^{+}_{s,p}(z)\right|^{2}}{dz} = g_{p}\left(\hbar\omega_{s}\right)\left|E^{+}_{s,p}(z)\right|^{2}$$

To model the amplified spontaneous emission, we use a **spectral slicing** scheme.

ASE is split into a many slices with photon energy

$$\hbar\omega_k = E_0 + k\,dE$$

Traveling-wave equations for the forward and backward propagating ASE

$$\frac{dN^{\pm}_{p,k}}{dz} = \pm g_p\left(\hbar\omega_k, n\right)N^{\pm}_{p,k} \pm R_{sp,p}\left(\hbar\omega_k, n\right)$$

Spontaneously emitted noise coupled into $N^{\pm}_{p,k}$ is given by

$$R_{sp,p}\left(\hbar\omega_k, n\right) = \Gamma_p(z)\,g_{sp,p}\left(\hbar\omega_k, n\right)dE/h$$

- The carrier density *n* at position z in the SOA is determined from the steady-state solution to the rate equation.

$$\frac{dn}{dt} = \boxed{\begin{aligned} &\frac{\eta(z) I}{ed\left[W_c\left(L_t + L_c\right) + W_t L_t\right]} - R(n) - \frac{\Gamma_{s,p}}{dW(z)} g_p\left(\hbar\omega_s, n\right)\left|E^+_{s,p}(z)\right|^2 \\ &- \frac{1}{dW(z)} \sum_{p=TE,TM} \sum_{k=0}^{N_s} \Gamma_p(z) g_p\left(\hbar\omega_k, n\right)\left[N^+_{p,k}(z) + N^-_{p,k}(z)\right] \end{aligned}}$$

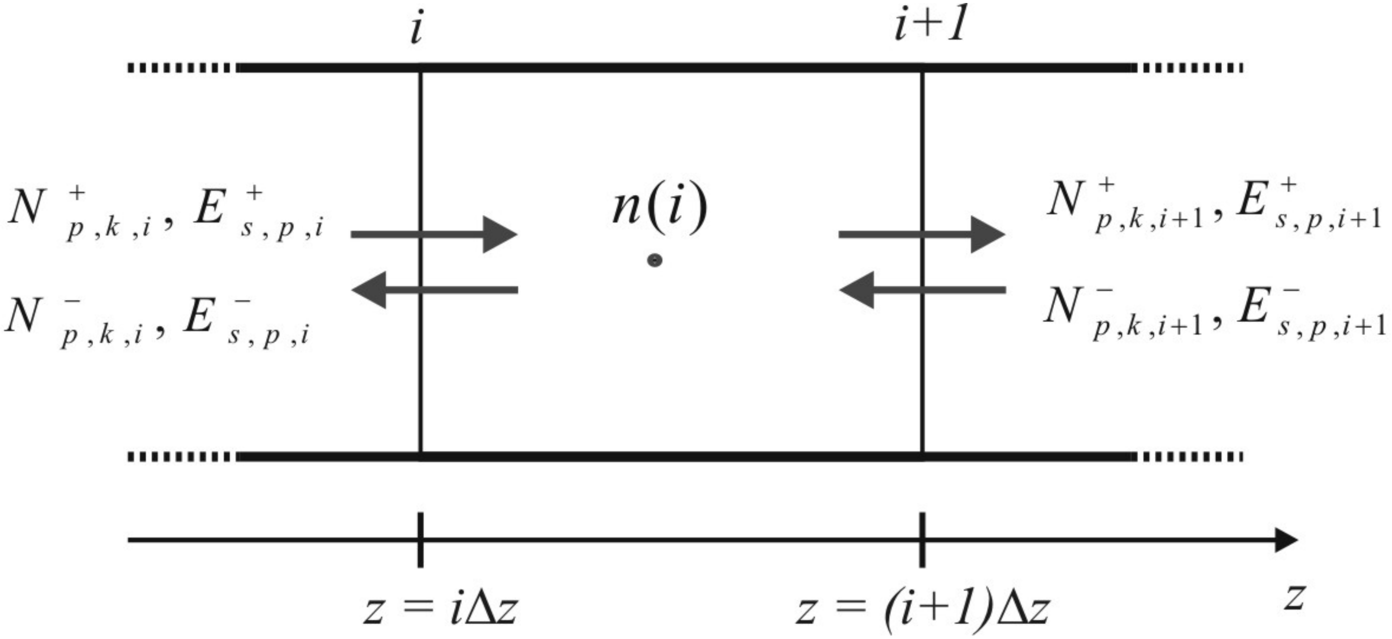
Q

Total quantum efficiency η = transport efficiency x pump blocking efficiency (depends on *n*)

Carrier recombination rate $R(n) = A_{tr} n + R_{rad}(n) + C_{aug} n^2$

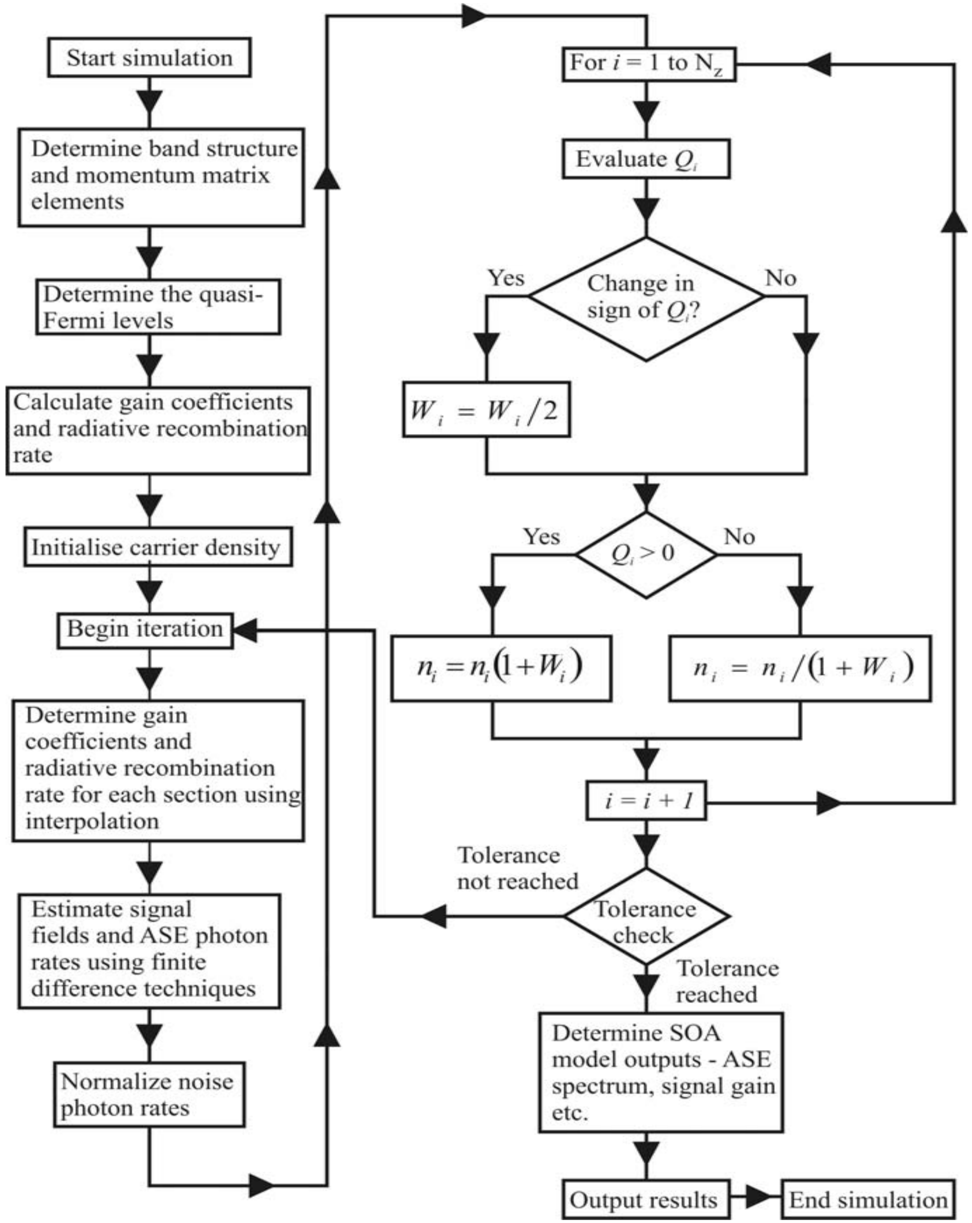
Numerical algorithm

- SOA is split into a number of spatial sections.



Numerical algorithm adjusts the carrier density such that $Q \longrightarrow$ zero for all sections

Flowchart


Start simulation
Determine band structure and momentum matrix elements
Determine the quasi-Fermi levels
Calculate gain coefficients and radiative recombination rate
Initialise carrier density
Begin iteration
Determine gain coefficients and radiative recombination rate for each section using interpolation
Estimate signal fields and ASE photon rates using finite difference techniques
Normalize noise photon rates
For $i = 1$ to N_z
Evaluate Q_i
Change in sign of Q_i?
Yes
No
$W_i = W_i / 2$
$Q_i > 0$
Yes
No
$n_i = n_i(1 + W_i)$
$n_i = n_i / (1 + W_i)$
$i = i + 1$
Tolerance not reached
Tolerance check
Tolerance reached
Determine SOA model outputs - ASE spectrum, signal gain etc.
Output results
End simulation

Simulations

- Momentum integral – trapezoidal integration with 400 points (k range from 0 to 2×10^9 m^{-1}) ; angle integral with 12 points.
- 30 spatial sections, 40 spectral slices.
- Model input parameters – all are known with reasonable accuracy except the
  - Molar fraction of As in the active region.
  - Effective strain
  - Effective intraband lifetime
  - Auger recombination coefficient

- The value of this parameter set for a given SOA is determined by using a parameter extraction algorithm that uses experimental polarization resolved ASE spectrum measurements at different bias currents.

- Based on the Levenberg-Marquardt method, which is used to determine the SOA parameters that minimize the merit factor*.

$$\chi = \frac{1}{N_{\exp t}} \sum_{l=1}^{N_{\exp t}} \frac{1}{2} \sum_{p=TE,TM} \sqrt{\frac{1}{N_s} \sum_{k=1}^{N_s} \left| P_{ASE,p,l}\left(\hbar\omega_k\right) - P_{\exp t,p,l}\left(\hbar\omega_k\right) \right|^2}$$

Extracted strain = 0.15% and effective intraband lifetime = 25 ps.

*M. Connelly, 'Semiconductor Optical Amplifier Parameter Extraction …..' *NUSOD, 2004**

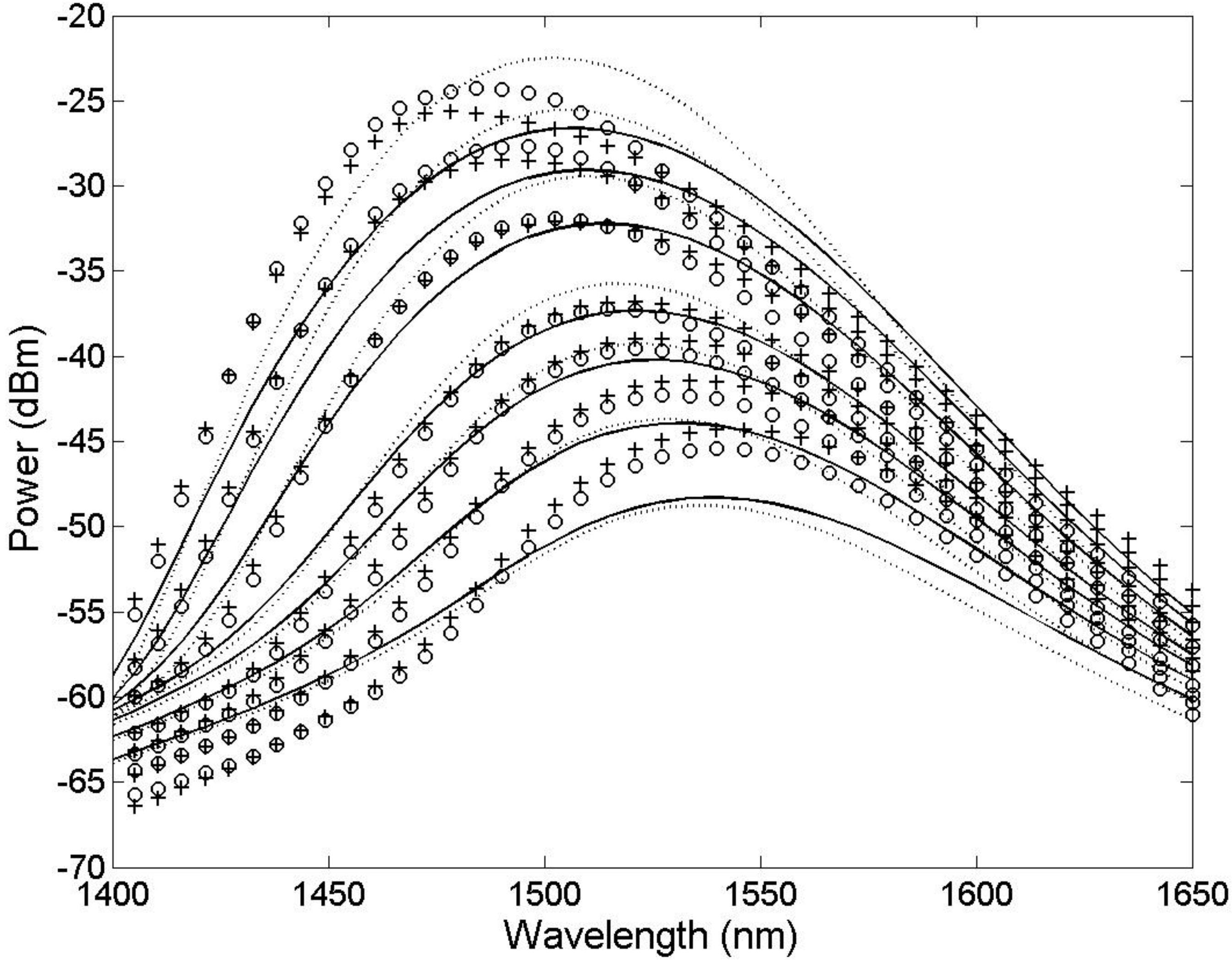
M. Connelly, '…..' *IEEE J. Quantum Electron*, to be published

- Matlab code.

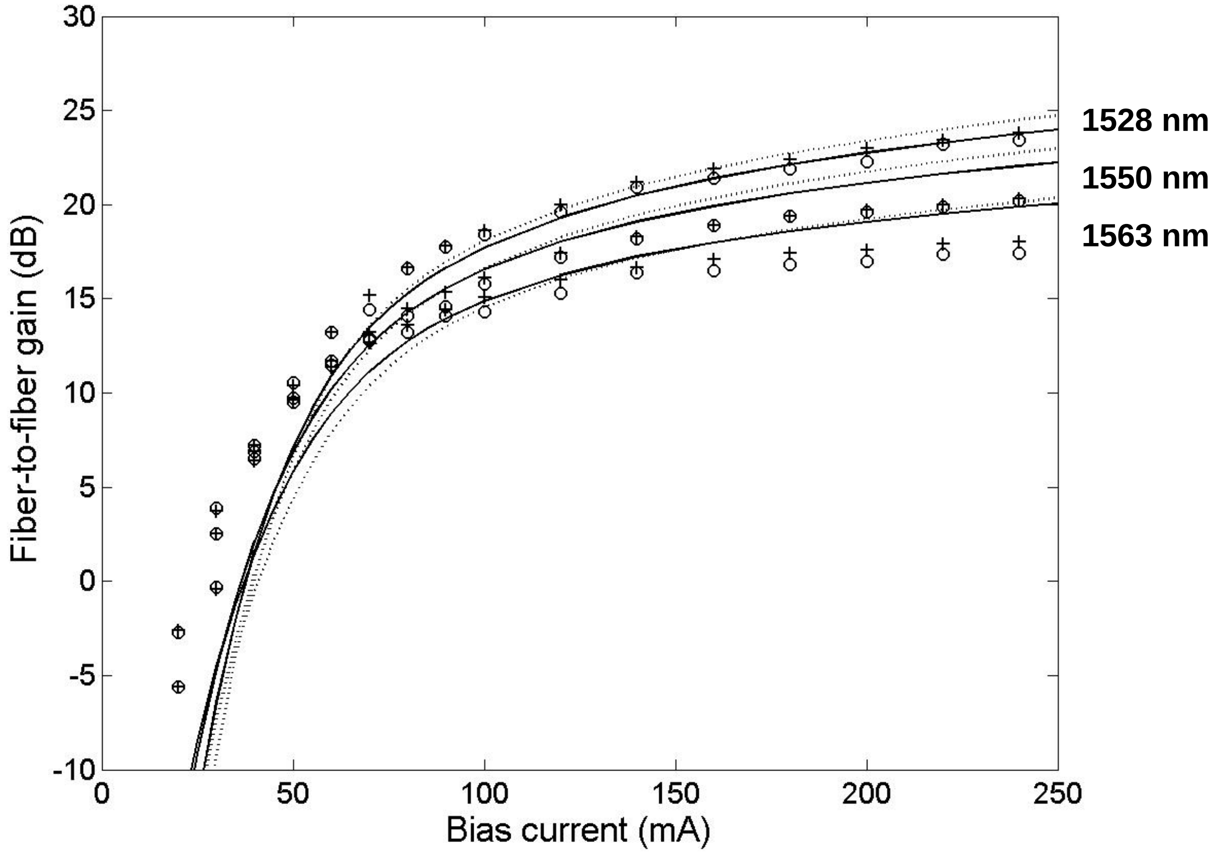
- Simulation times

Typical single-point simulation (bias and input signal power fixed) – 10 s.

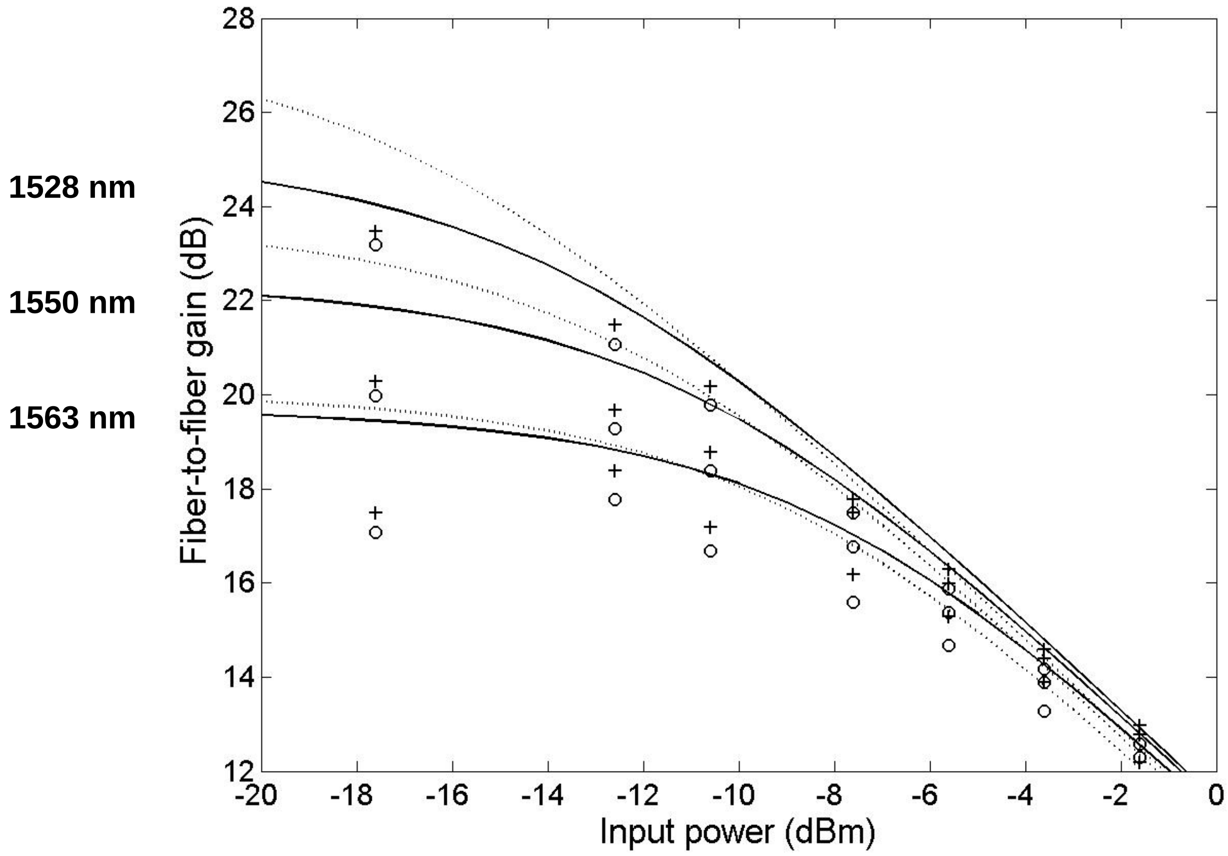
Typical parameter extraction run – for 6 bias currents and converging to < 2.5 dB difference between experiment and simulation – 15 mins.



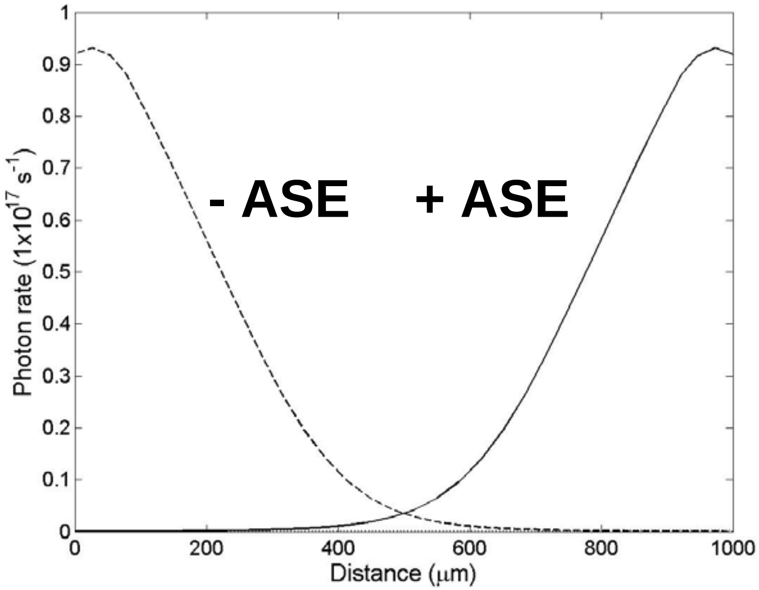
Experimental and simulated SOA output polarization resolved ASE spectra. The bias currents are 40, 50, 60, 70, 100, 140, and 200 mA

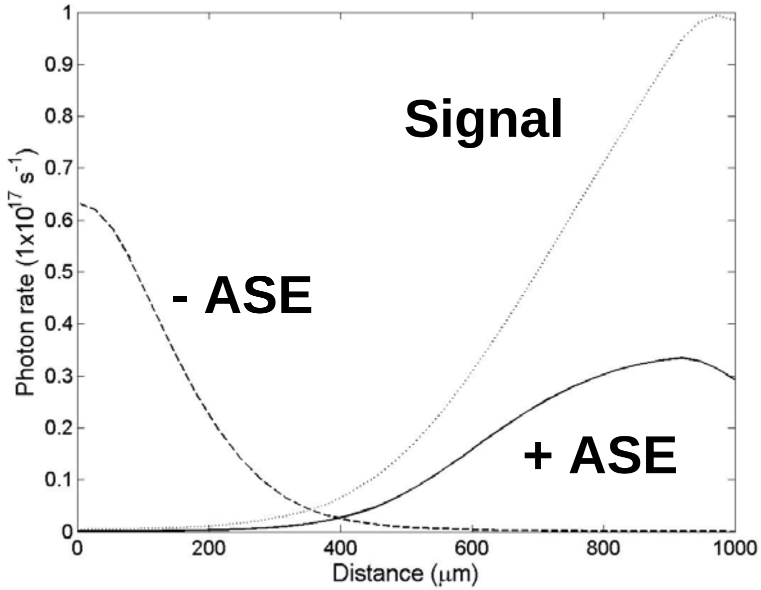


Experimental and simulated polarisation resolved fiber-to-fiber gain versus bias current, with an input signal power of –14 dBm



Experimental and simulated fiber-to-fiber gain versus input power at a bias current of 200 mA.

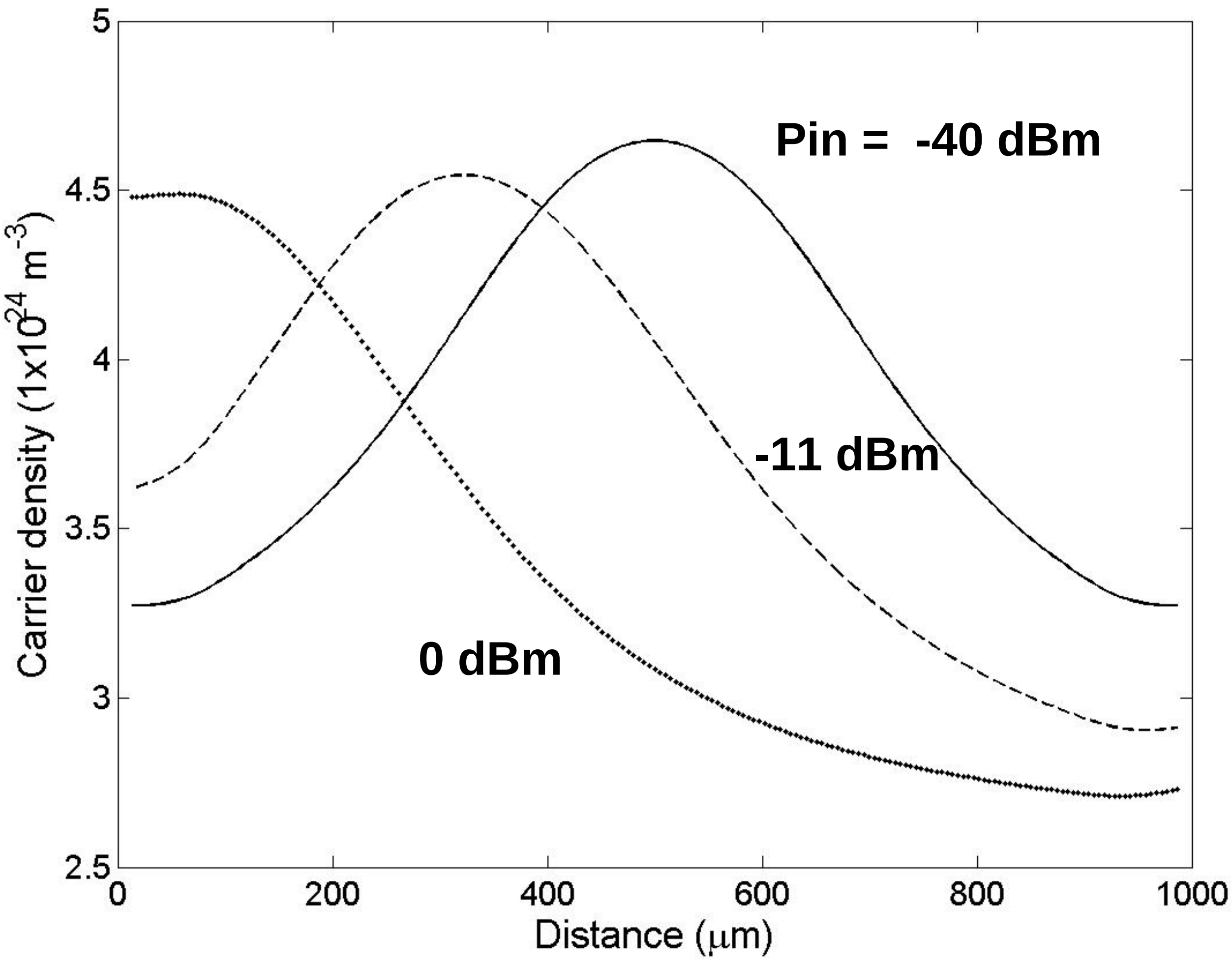




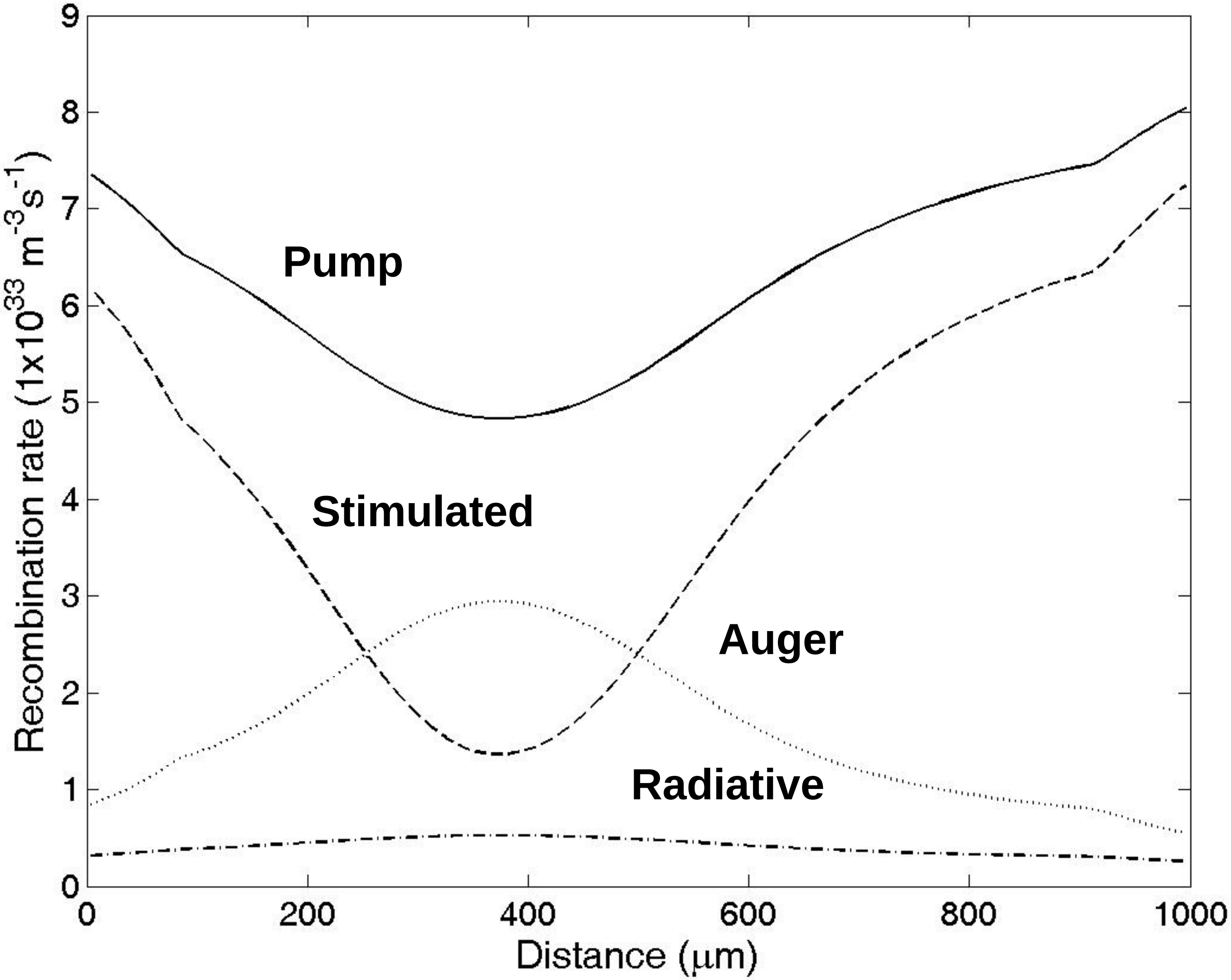
(a) Pin = -40 dBm

(b) Pin = -11 dBm

ASE and signal spatial distributions.



Simulated carrier density spatial distributions for TM polarized signal input powers. Bias current = 200 mA. Wavelength = 1550 nm



Pump and recombination terms on the RHS of carrier density rate equation. Bias current = 200 mA and input signal power = -11 dBm;

Conclusion

- A wideband steady-state model of a tensile-strained bulk SOA has been described.
- The model predictions show good agreement with experiment. Parameter extraction required.
- The model can be used to investigate the effects of different material and geometrical parameters on SOA performance under operating conditions ranging from low and high bias currents and input signal powers and over a wide range of signal wavelengths.