Numerical Analysis of Pulse Pedestal and Dynamic Chirp Formation on Picosecond Modelocked Laser Pulses after Propagation through a Semiconductor Optical Amplifier

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Outline

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3. Numerical model
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Introduction

SOAs have attracted much interest both as basic amplifiers and also in all-optical signal processing applications such as all-optical clock recovery and time division demultiplexing.

Common pulse sources used in ultra-fast optical communications include:

- Mode locked lasers
- Gain switched lasers
- CW lasers followed by electro-absorption modulators.

These sources can generate high quality pulses that exhibit low chirp, jitter and high temporal and spectral purity.

- Mode locked laser pulse sources can exhibit pedestals at either side of the main pulse*.

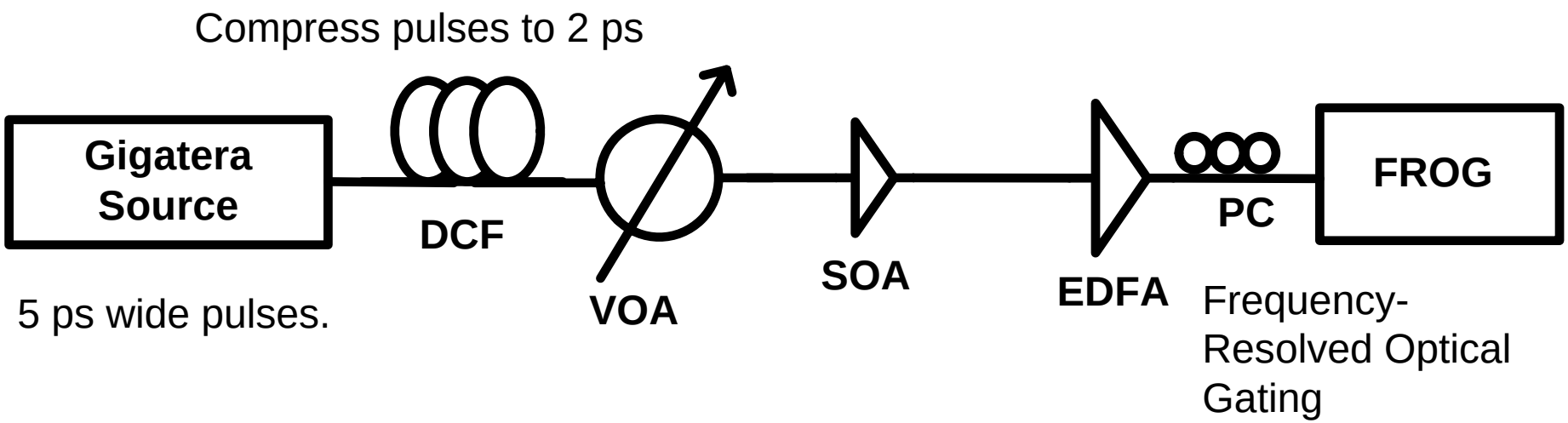
- The pedestals are usually at a power level > 40 dB below the main pulse.

- When amplified by an SOA, the pedestal power will increase relative to the main pulse due to dynamic SOA gain saturation. This can lead to interchannel crosstalk in optical TDM systems.

- We present experimental results and numerical simulations on the propagation of 2 ps wide mode-locked laser pulses after propagation through an SOA.

*J.M. Dudley at al, Quantum Semiclass. Opt. **8** (1996) pp. 1029-1039.

Experiment



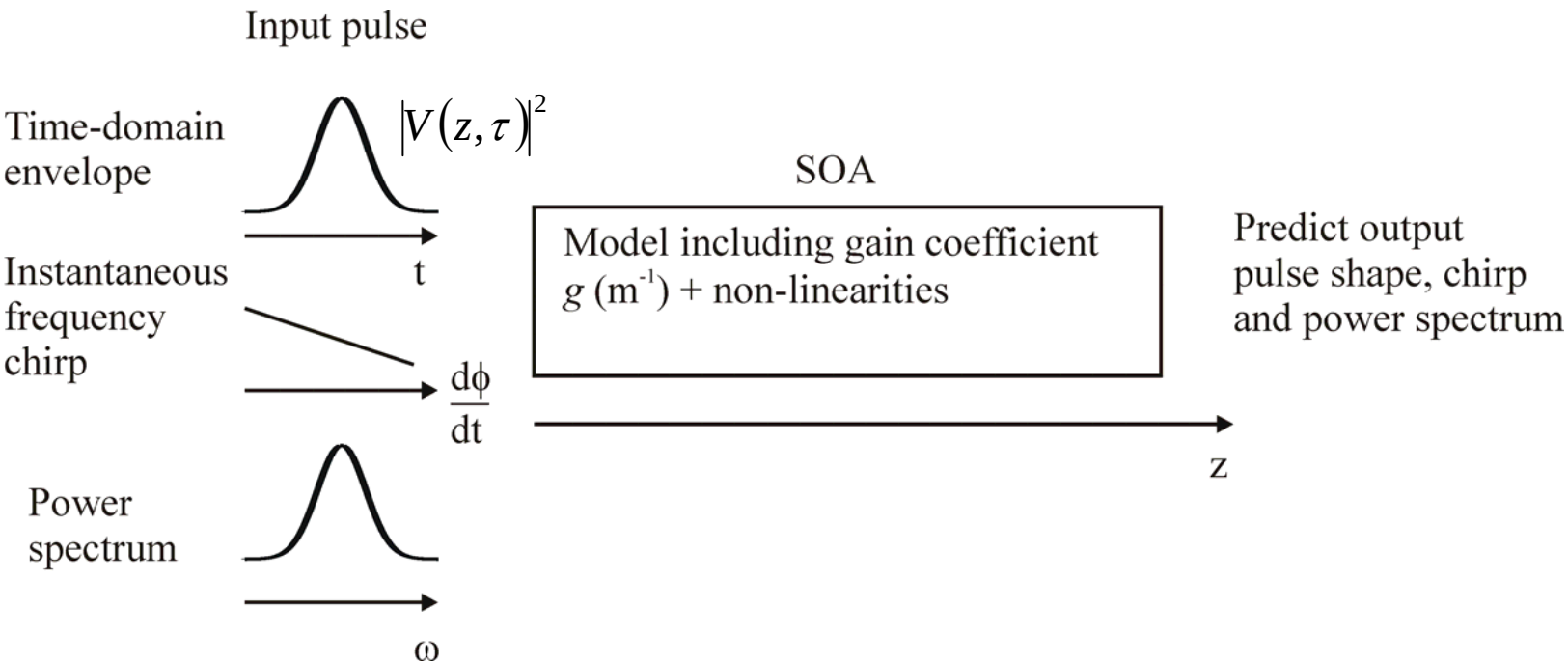
FROG technique* – allows measurement of the intensity and phase of an optical pulse.

Commercial SOA (Kamelian) – 920 μm long. Tensile-strained bulk material.

*R. Trebino, 'Frequency-Resolved Optical Gating: The Measurement of Ultrashort Laser Pulses'; Springer, 2000.

A. Clark, M. Connelly et al, *IEEE Photon. Tech. Lett.,* Sept. 2005.

Numerical Model



Require equations to model propagation of the time-domain complex envelope of the optical pulse V(z,τ).

Local time $\tau = t - z/v_g$

Use model based on a modified Schrödinger equation, which includes nonlinearities induced by gain saturation, two-photon absorbtion and carrier heating*.

$$\frac{\partial V(z,\tau)}{\partial z} = \left[\frac{1}{2} g_N(\tau,\omega_0)(1+i\alpha_N) + \frac{1}{2}\Delta g_T(\tau,\omega_0)(1+i\alpha_T) - \frac{i}{2}\frac{\partial g(\tau,\omega)}{\partial \omega}\bigg|_{\omega_0}\frac{\partial}{\partial \tau} - \frac{1}{4}\frac{\partial^2 g(\tau,\omega)}{\partial^2 \omega}\bigg|_{\omega_0}\frac{\partial^2}{\partial \tau^2} - \frac{\gamma}{2} - \left(\frac{\gamma_2}{2} + ib_2\right)\left|V(z,\tau)\right|^2 \right] V(z,\tau)$$

Modified Schrödinger equation

$$g_N(\tau) = g_0 \exp\left[-\frac{1}{W_s}\int_{-\infty}^{\tau} e^{-\frac{\tau'}{\tau_s}} \left|V(\tau')\right|^2 d\tau' \right]$$

Carrier density induced non-linearly saturating gain – also leads to self phase modulation via α_N (linewidth enhancement factor).

g_0 – unsaturated gain coefficient, W_s – SOA saturation energy.

*M.J. Hong et al., *IEEE J. Quantum Electron,* April 1994 & Bogoni at al, *IEEE J. Quantum Electron.* 2004.

$$\Delta g_T(\tau,\omega_0) = -\int_0^\infty U(s)e^{-s/\tau_{ch}}\left[h_1\left|V(\tau-\tau')\right|^2 + h_2\left|V(\tau-\tau')\right|^4\right]\left(1-e^{-\tau'/\tau_{\text{int}}}\right)d\tau'$$

Non-linear gain caused by carrier heating due to combined effects of stimulated emission, free carrier absorption (h_1) and two-photon absorption (h_2)

$$\left.\frac{\partial g(\tau,\omega)}{\partial\omega}\right|_{\omega_0} = A_1 + B_1\left[g_0 - g(\tau,\omega_0)\right]$$

Dynamically varying slope and curvature of the gain coefficient.

$$\left.\frac{\partial^2 g(\tau,\omega)}{\partial^2\omega}\right|_{\omega_0} = A_2 + B_2\left[g_0 - g(\tau,\omega_0)\right]$$

where $g(\tau,\omega_0) = g_N(\tau,\omega_0) + \Delta g_T(\tau,\omega_0)$

$$-\frac{\gamma}{2}$$

Material loss coefficient.

$$\left(\frac{\gamma_2}{2}+ib_2\right)\left|V(\tau,z)\right|^2$$

Two photon absorption and the non-linear Kerr effect.

- The model contains a large number of parameters.

  Obtain $g_0, A_1, B_1, A_2, B_2, W_s, \alpha_N, \alpha_T, \gamma$

  from theoretical SOA material gain calculations and using a steady-state wideband model*.

M.J. Connelly, *IEEE J. Quantum Electron*., 2001.

- The material gain calculations were carried out using a 6x6 **k**·**p** Hamiltonian that includes the split-off band.

- Band-tail effects are included in the gain calculations.

- The material gain spectra were then used in the steady-state model to predict the SOA output amplified spontaneous emission spectra at different bias currents.

- Agreement between predicted and measured ASE spectra was obtained by extracting the Auger recombination coefficient, material loss coefficient and the trap recombination coefficient.

- It is then possible to determine the SOA carrier density for a given bias current and hence

$$g_0, A_1, B_1, A_2, B_2, W_s, \alpha_N, \alpha_T$$

- The remaining parameters must be obtained by comparing the dynamic experimental results with the model.

The modified Schrödinger equation is a non-linear p.d.e., which in general does not have an analytical solution.

We use the split-step Fourier method – fast because it uses the Fast Fourier Transform (FFT).

The MSE can be written in the form $\frac{\partial V}{\partial z} = \left(\hat{D} + \hat{N}\right) V$

With linear and non-linear operators

$$\hat{D} = -\frac{\gamma}{2} - \frac{i\left(A_1 + B_1 g_0\right)}{2}\frac{\delta}{\delta\tau} - \frac{\left(A_2 + B_2 g_0\right)}{4}\frac{\delta^2}{\delta\tau^2}$$

$$\hat{N} = \frac{1}{2} g_N\left(\tau,\omega_0\right)\left(1 + i\alpha_N\right) + \frac{1}{2}\Delta g_T\left(\tau,\omega_0\right)\left(1 + i\alpha_T\right) - \frac{iB_1 g\left(\tau,\omega_0\right)}{2}\frac{1}{V\left(\tau,z\right)}\frac{\partial V\left(\tau,z\right)}{\partial\tau}$$
$$+ \frac{B_2 g\left(\tau,\omega_0\right)}{4}\frac{1}{V\left(\tau,z\right)}\frac{\partial^2 V\left(\tau,z\right)}{\partial\tau^2} - \left(\frac{\gamma_2}{2} + ib_2\right)\left|V\left(\tau,z\right)\right|^2$$

The split-step Fourier method obtains an approximate solution by assuming that in propagating the optical field over a short distance Δz the linear and nonlinear effects act independently. So we can write

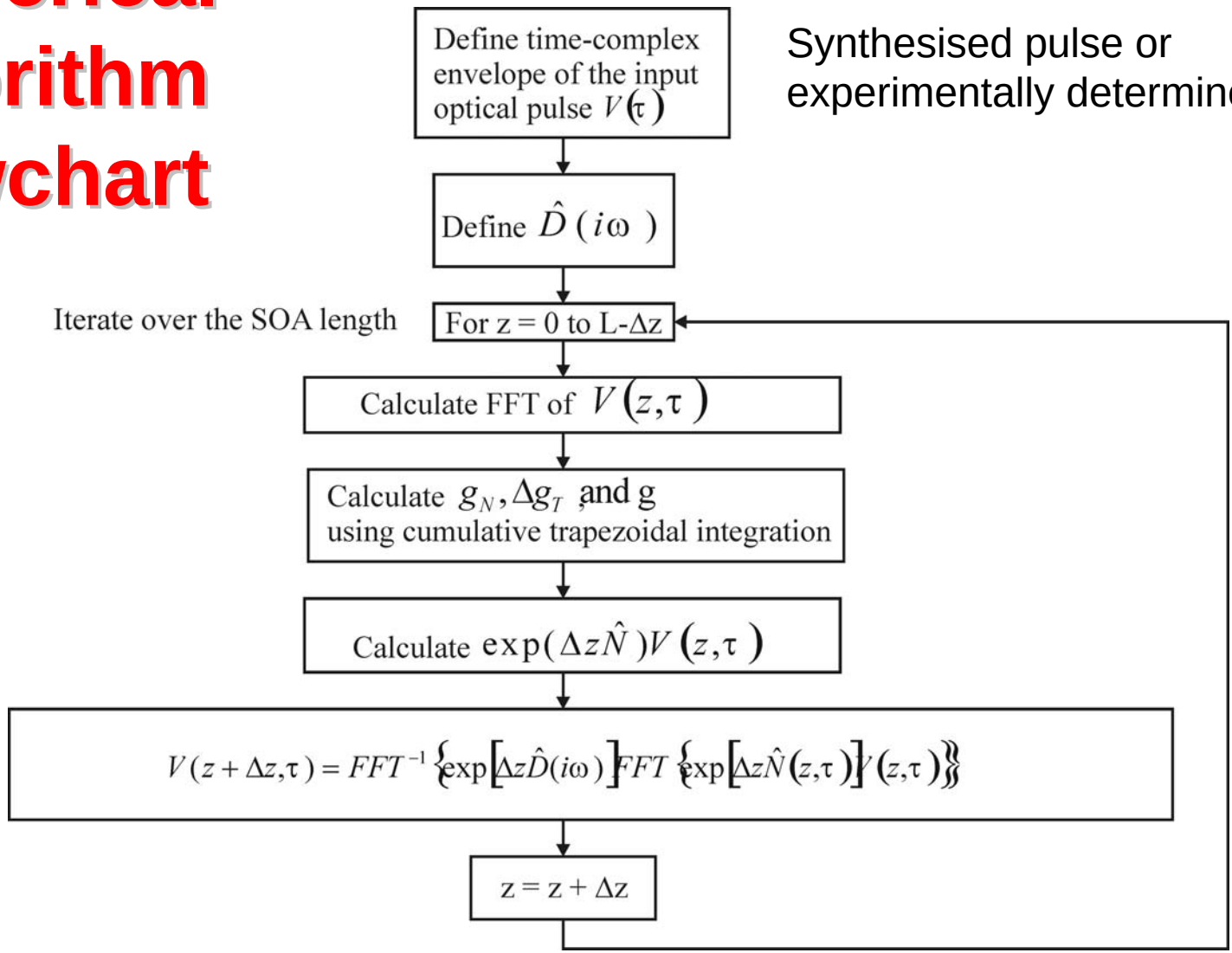
$$V(z+\Delta z,\tau) \approx \exp\left(\Delta z \hat{D}\right)\exp\left(\Delta z \hat{N}\right) V(z,\tau)$$

The operator $\exp\left(\Delta z \hat{D}\right)$ can be evaluated in the frequency domain according to

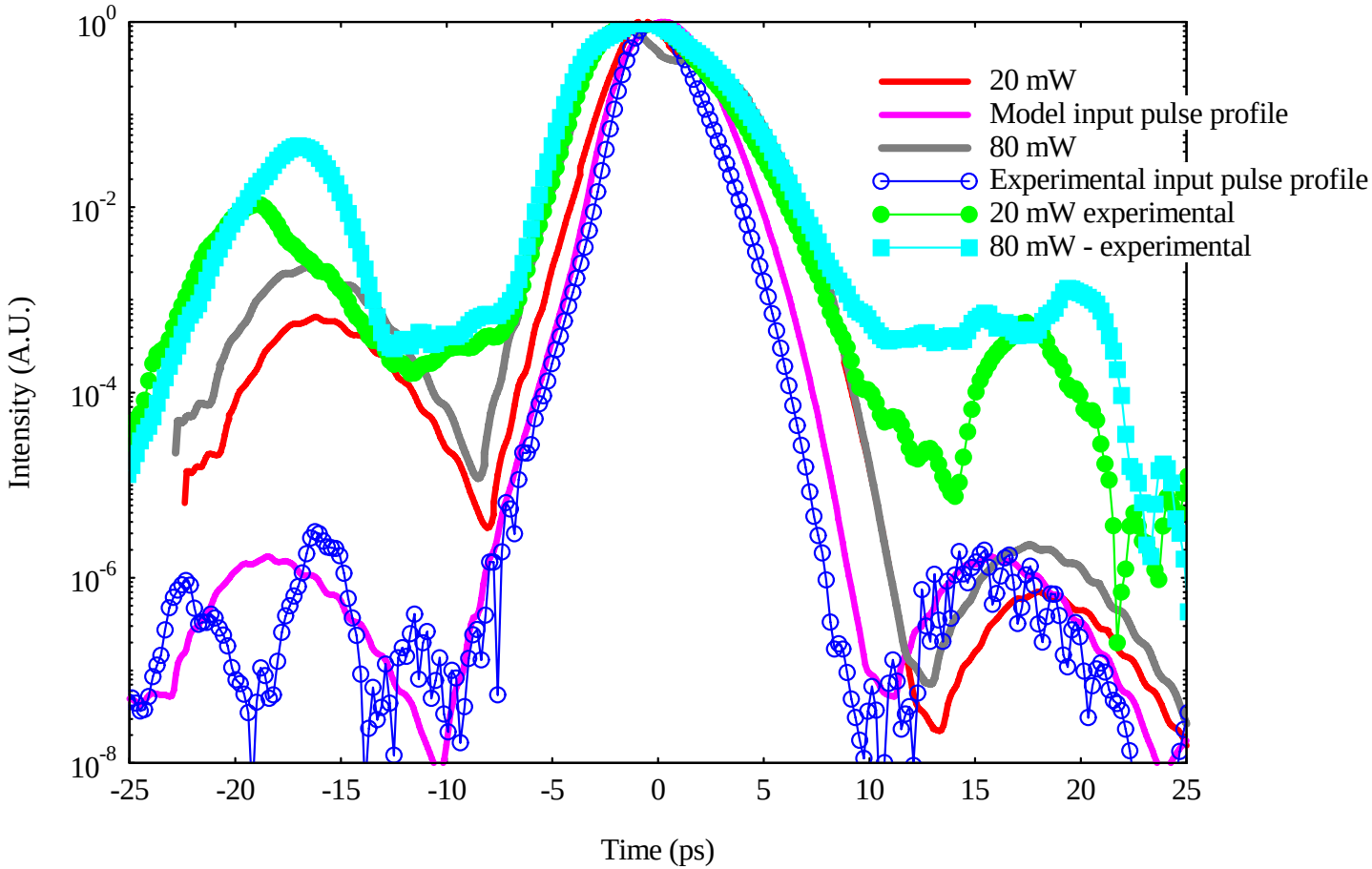
$$\exp\left(\Delta z \hat{D}\right) y(z,\tau) = F_T^{-1}\left\{\exp\left[\Delta z \hat{D}(i\omega)\right] F_T\left\{y(z,\tau)\right\}\right\}$$

Numerical Algorithm Flowchart

Synthesised pulse or experimentally determined.

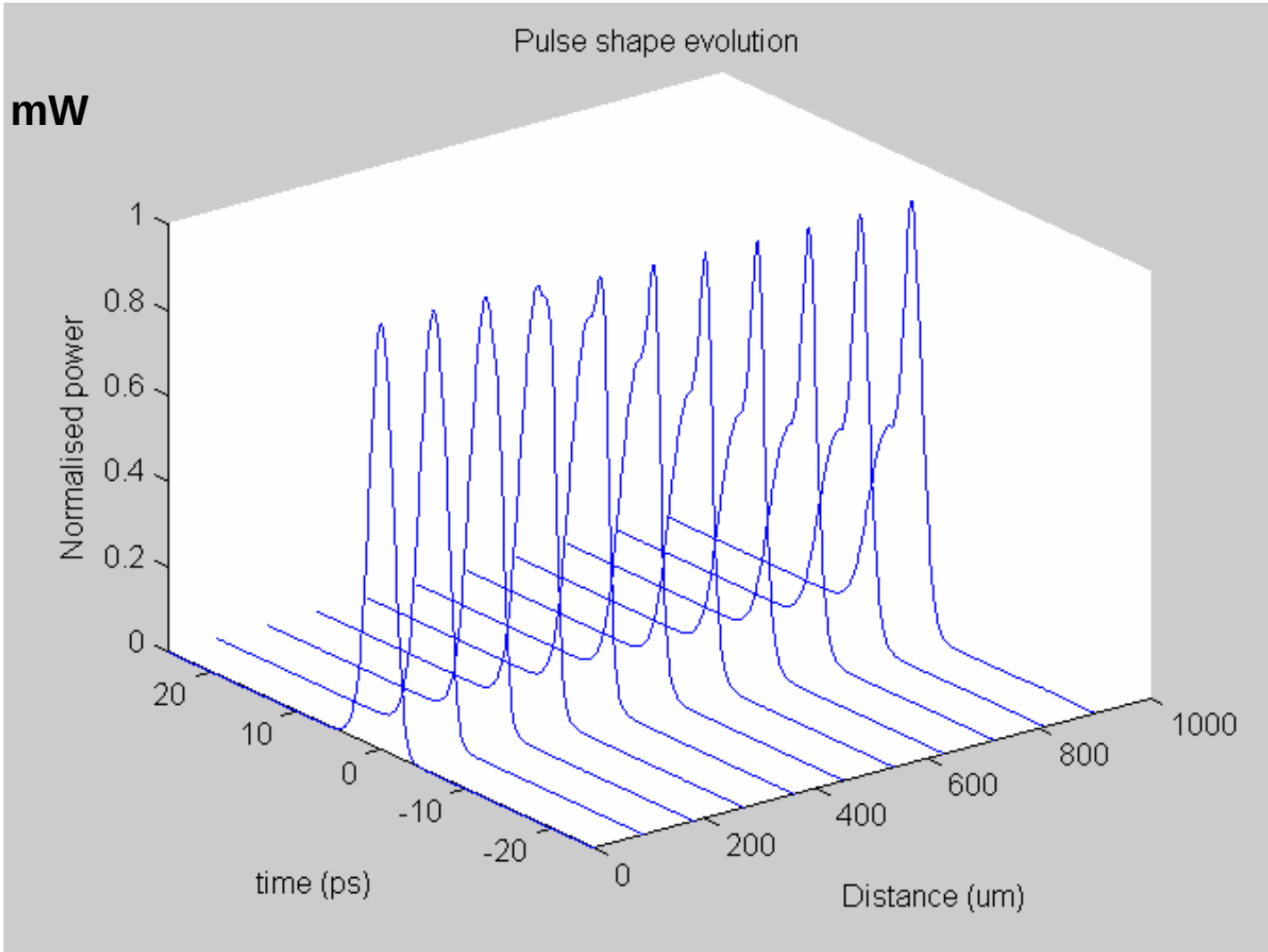


Results

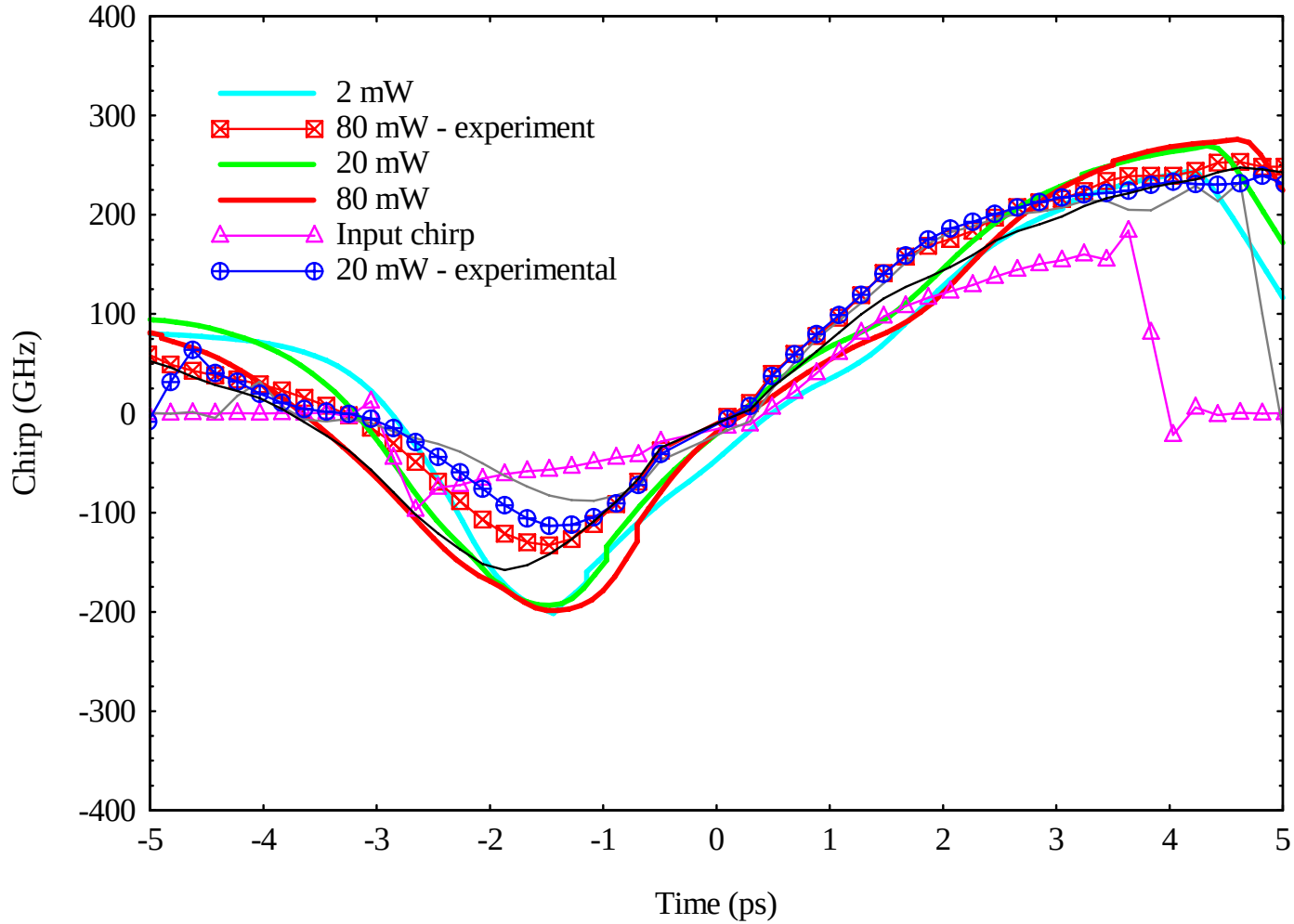


Pulse temporal profiles

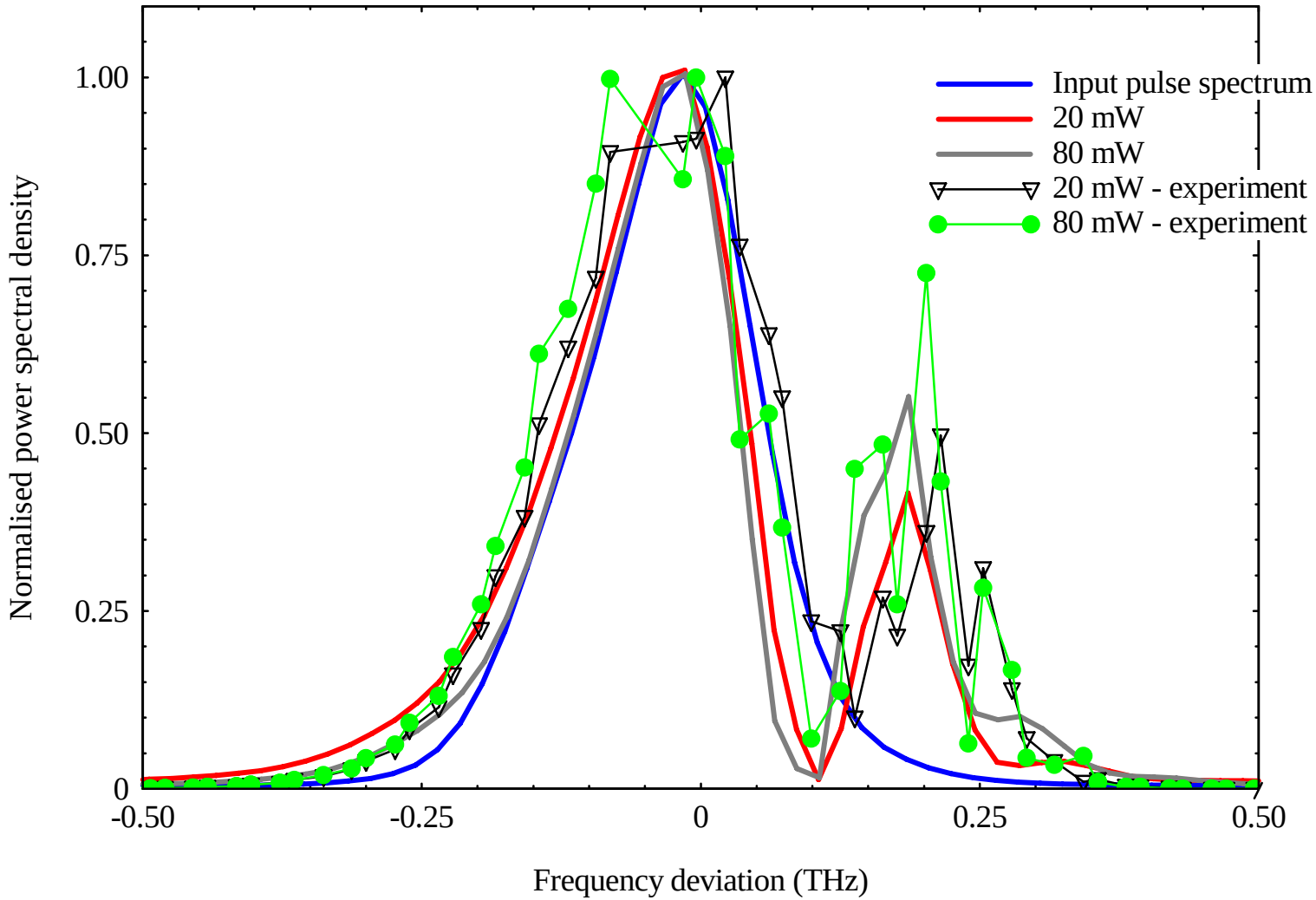
Pin = 80 mW



Pulse evolution

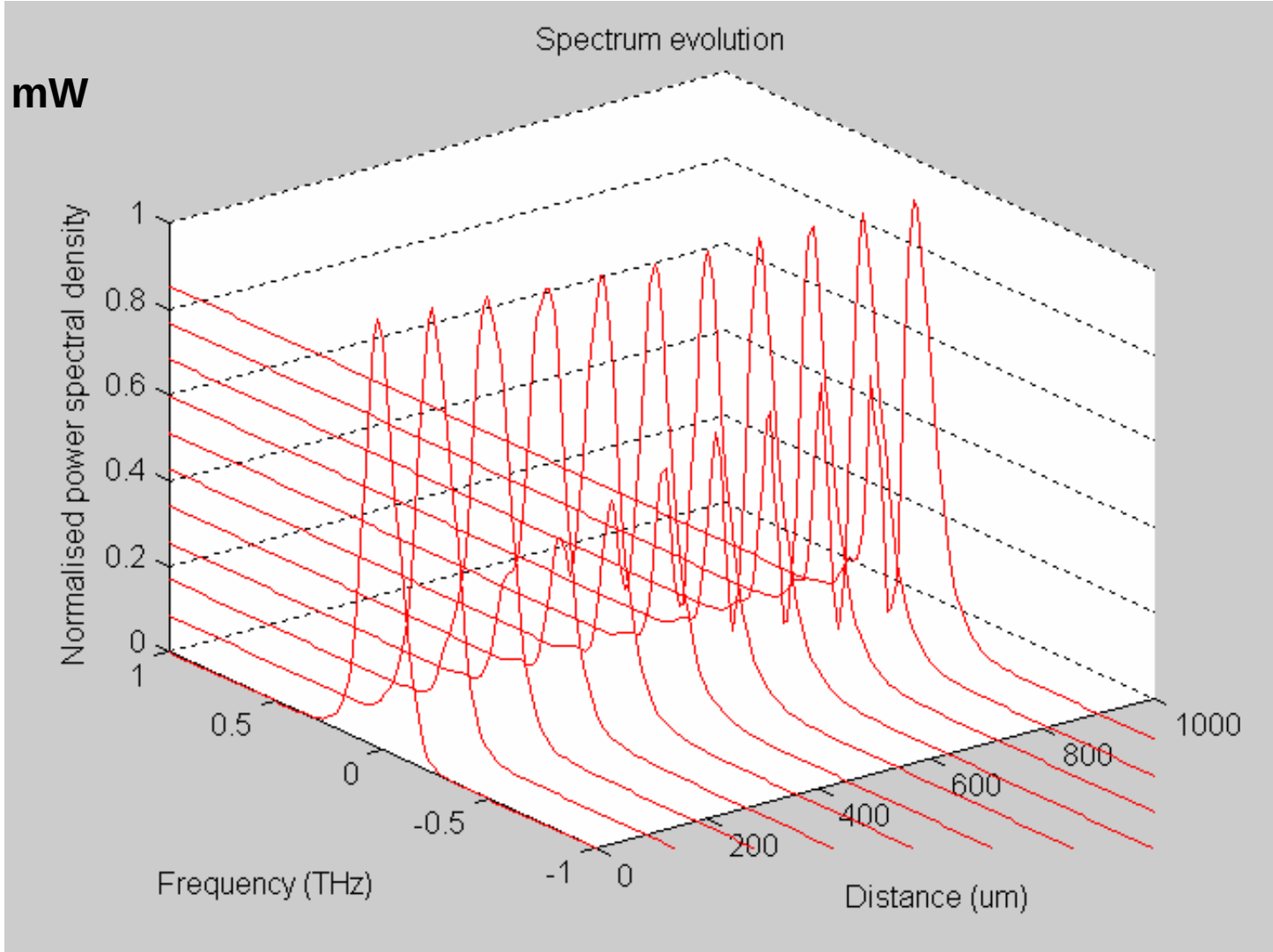

2 mW
80 mW - experiment
20 mW
80 mW
Input chirp
20 mW - experimental
Chirp (GHz)
Time (ps)
400
300
200
100
0
-100
-200
-300
-400
-5
-4
-3
-2
-1
0
1
2
3
4
5

Pulse chirp



Pulse spectrum

Pin = 80 mW



Spectrum evolution

Conclusions

- Experimentally – pedestals present on mode-locked laser pulses can be significantly amplified with respect to the main pulse.

- Used a dynamic numerical model, including detailed calculation of the material gain spectra, to enable reasonable prediction of the pulse amplification, dynamic chirp and pulse spectrum.

- However the model contains a lot of parameters.

- Future work will use a parameter extraction technique and the measured pulse temporal profile and dynamic chirp to estimate more accurately the parameters that determine the relative importance of the various non-linear mechanisms in the SOA.

Thank you for your attention.