

Simulation of semiconductor modelocked ring lasers with monolithically integrated pulse shaping elements

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COST Action 288

Introduction to technology and motivation

Modelocked ring laser model
options for the realisation of a fs laser

Modelocked ring laser bidirectional model

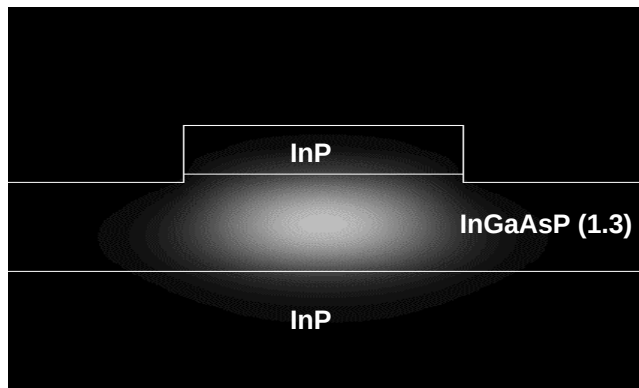


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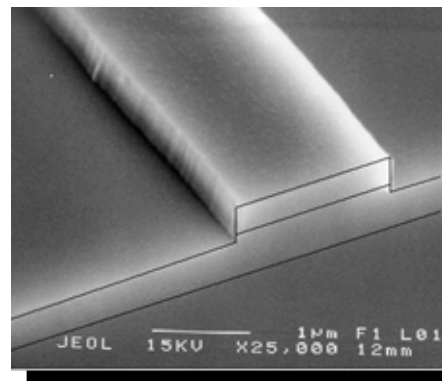


FREEBAND

Passive Waveguide Devices + Semiconductor Optical Amplifier + EO Phase Modulator

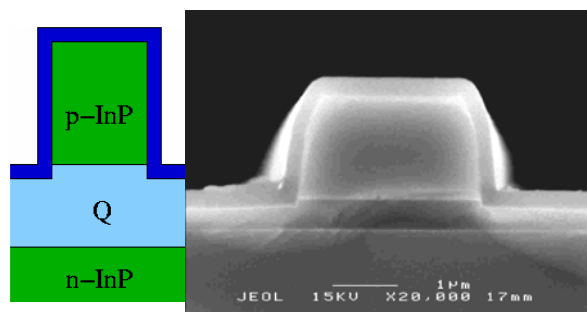


Light field

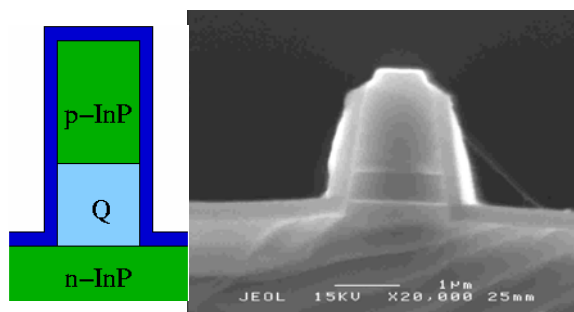


Loss $\leq 1\text{dB/cm}$

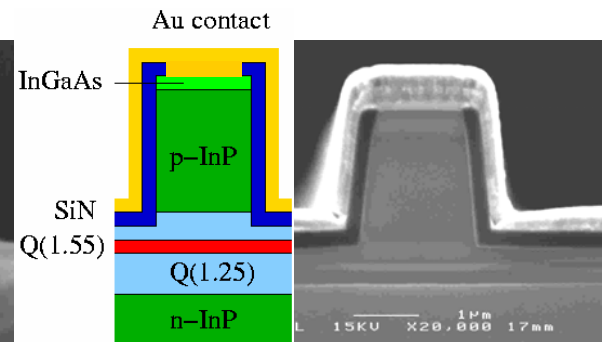
Waveguide



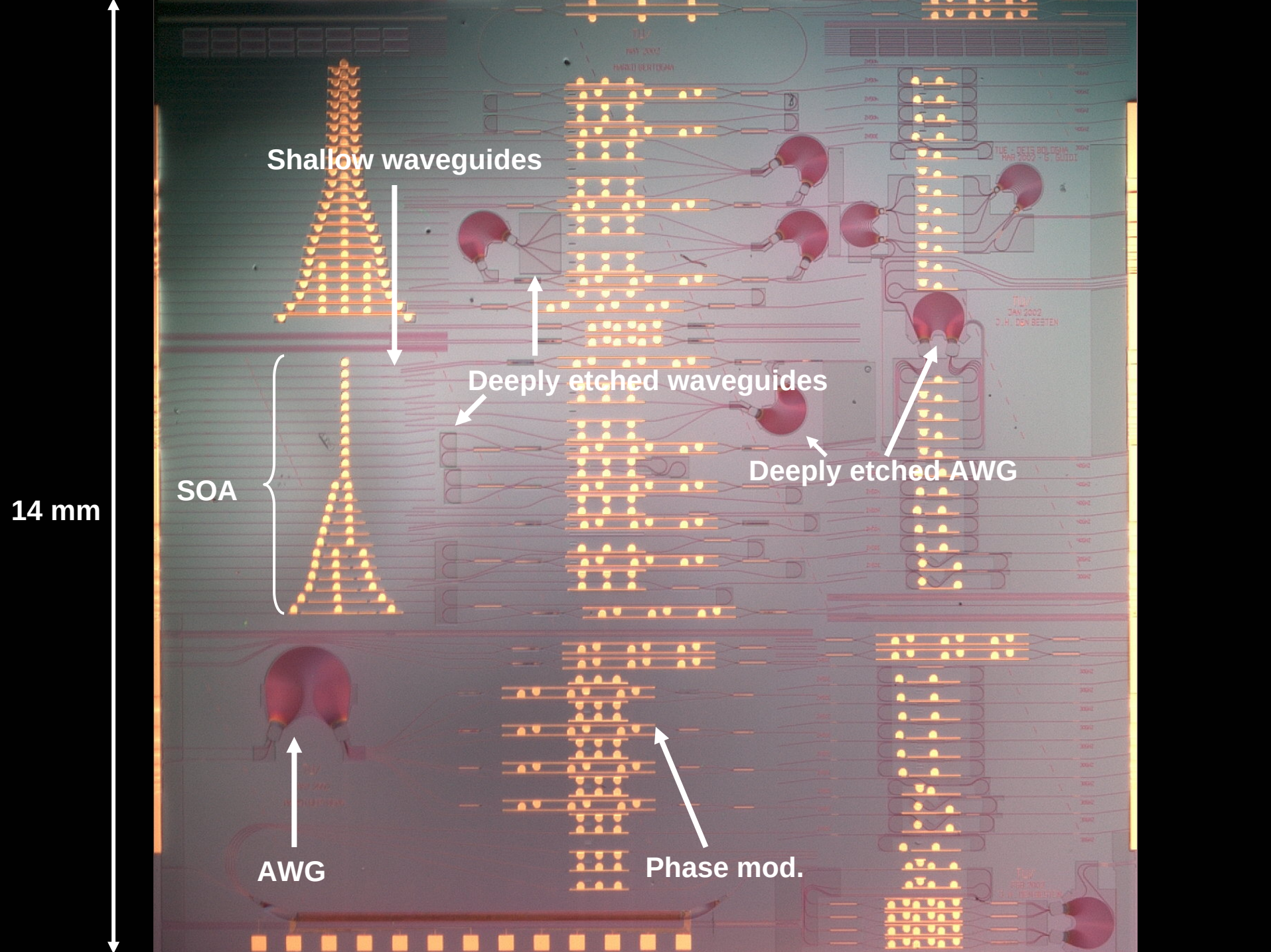
Shallowly-etched



Deeply-etched



SOA or
Sat. Abs.



Modelocking using a reversely biased SOA section
Slow saturable absorber modelocking

Application: all optical clock recovery (40GHz)

Ring laser configuration

lithographic control of the cavity length

injection locking

combination with other components (e.g. all-optical switches)

choose position of absorber – gain section

TU/e Passively modelocked lasers

Integrated femtosecond lasers

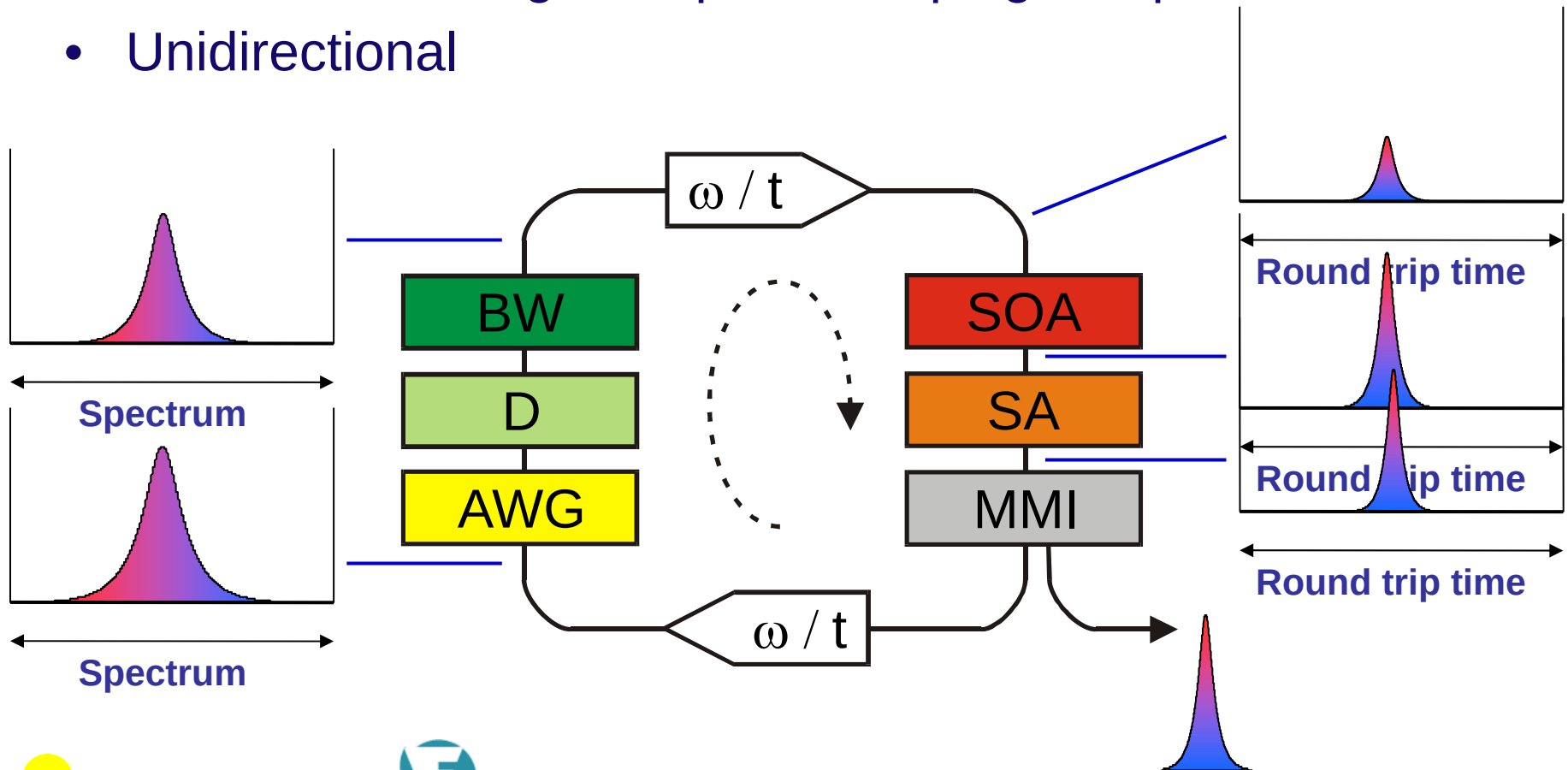
Applications: Telecommunication
 THz bit rate communication
 Multi-wavelength ps source
 OCDMA source
 High speed optical ADC
 Pulses with controlled amplitude and phase
 Sensing, imaging, coherent control

Approach: Dispersion control
 Self phase modulation
 compensating devices with(in) the laser

Building blocks are available → How do we put these together?

TU/e Modelling approach

- Model of modelocked ring laser
- AWG based integrated pulse shaping components
- Unidirectional



Optical pulse description

$$E(t) = \sqrt{P(t)} \exp(i\omega_0 t - i\phi(t))$$

Rate equations

[J.M. Tang and K.A. Shore IEE Proc. Optoelectron, Vol 146, No. 1, 1999]

$$G = \Gamma a_N (N - N_{tr}) \quad G_0 = -\Gamma a_N N_{tr} \left(\frac{I \tau_s}{q V N_{tr}} - 1 \right)$$

$$\frac{\partial G}{\partial t} = \frac{G_0 - G}{\tau_s} - \frac{1}{E_{sat}} \frac{G - \epsilon_2 P^2}{1 + \epsilon_1 P} P + \Gamma_2 \beta'_2 P^2$$

ϵ_1 Non-linear gain compression – carrier heating & spectral hole burning

ϵ_2 Gain compression due to two photon absorption

Power

$$\frac{\partial P}{\partial z} = \frac{G - \varepsilon_2 P^2}{1 + \varepsilon_1 P} P - 2\Gamma_2 \beta_2 \frac{1}{\sigma} P^2 - \alpha_{\text{int}} P$$

Phase

$$\frac{\partial \phi}{\partial z} = -\frac{1}{2} \left[\alpha_N G - \alpha_T \frac{\varepsilon_1 G P - \varepsilon_2 P^2}{1 + \varepsilon_1 P} \right] - \Gamma'_2 \frac{\omega_0}{c} n_2 \frac{1}{\sigma} P$$

α_N Carrier density linewidth enhancement factor

α_T Carrier temperature linewidth enhancement factor

n_2 Nonlinear refractive index

$$Q_0 = -\Gamma a_{N,SA} N_{tr,SA}$$

$$\frac{\partial Q}{\partial t} = \frac{Q_0 - Q}{\tau_{eff,SA}} - \frac{1}{E_{sat,SA}} \frac{Q}{1 + \varepsilon_{1,SA} Q} P$$

$$\frac{\partial P}{\partial z} = \frac{Q}{1 + \varepsilon_{1,SA} Q} P$$

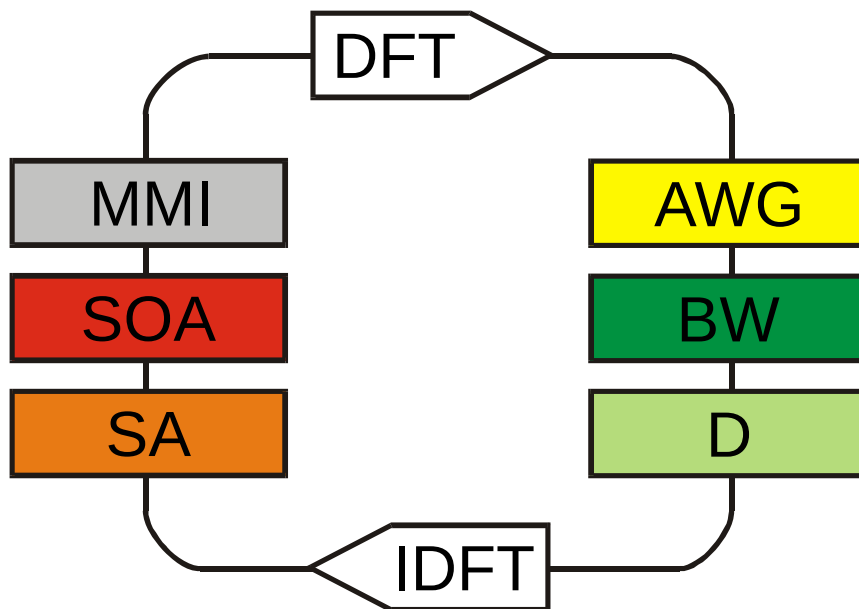
$$\frac{\partial \phi}{\partial z} = -\frac{1}{2} \alpha_{N,SA} Q$$

Effect of reverse bias on the diode in τ_{eff}

Ignored two photon absorption and fast non linear refraction.

Phase change due to carrier heating is ignored.

[Schell et al, IEEE J.QE, v32, p1180, 1996]



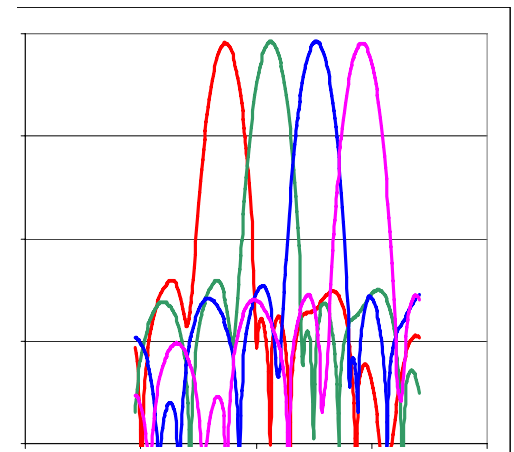
- Optical pulse description

$$E(t) = \sum_{n=-\infty}^{\infty} E_n \exp(i\omega_n t)$$

- Frequency filters (D)

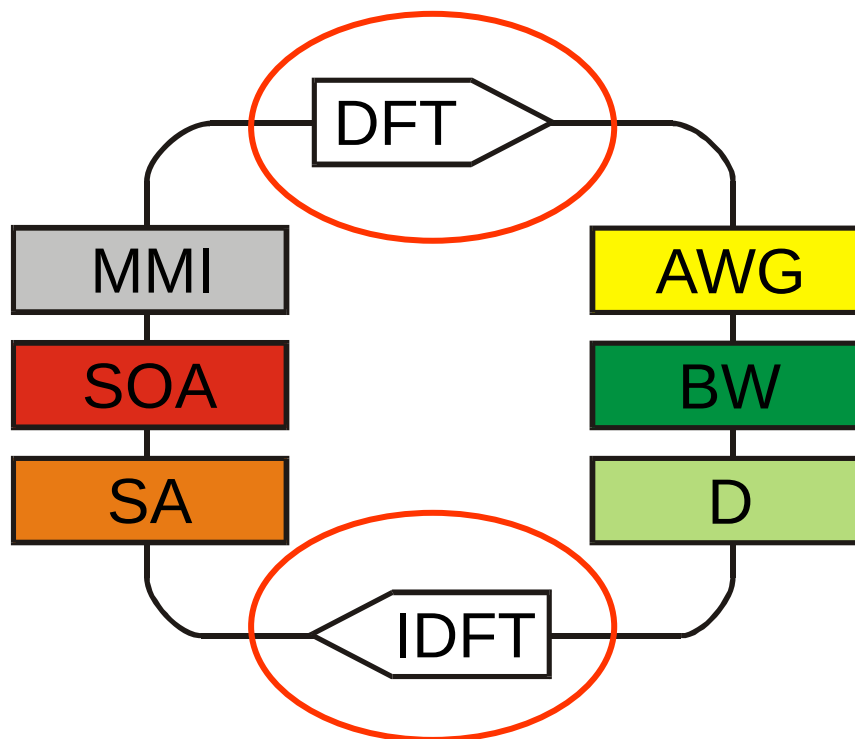
$$H(\omega) = \exp\left[-\frac{i}{2}k''_{tot}(\omega - \omega_0)^2\right]$$

(AWG)



$$E(t) = \sqrt{P(t)} \exp(i\omega_0 t - i\varphi(t))$$

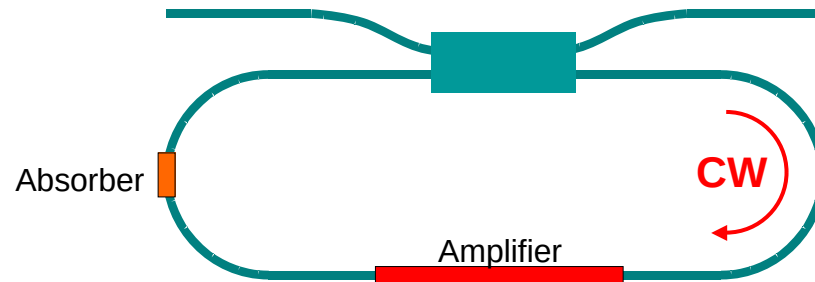
$$E(t) = \sum_{n=-\infty}^{\infty} E_n \exp(i\omega_n t)$$



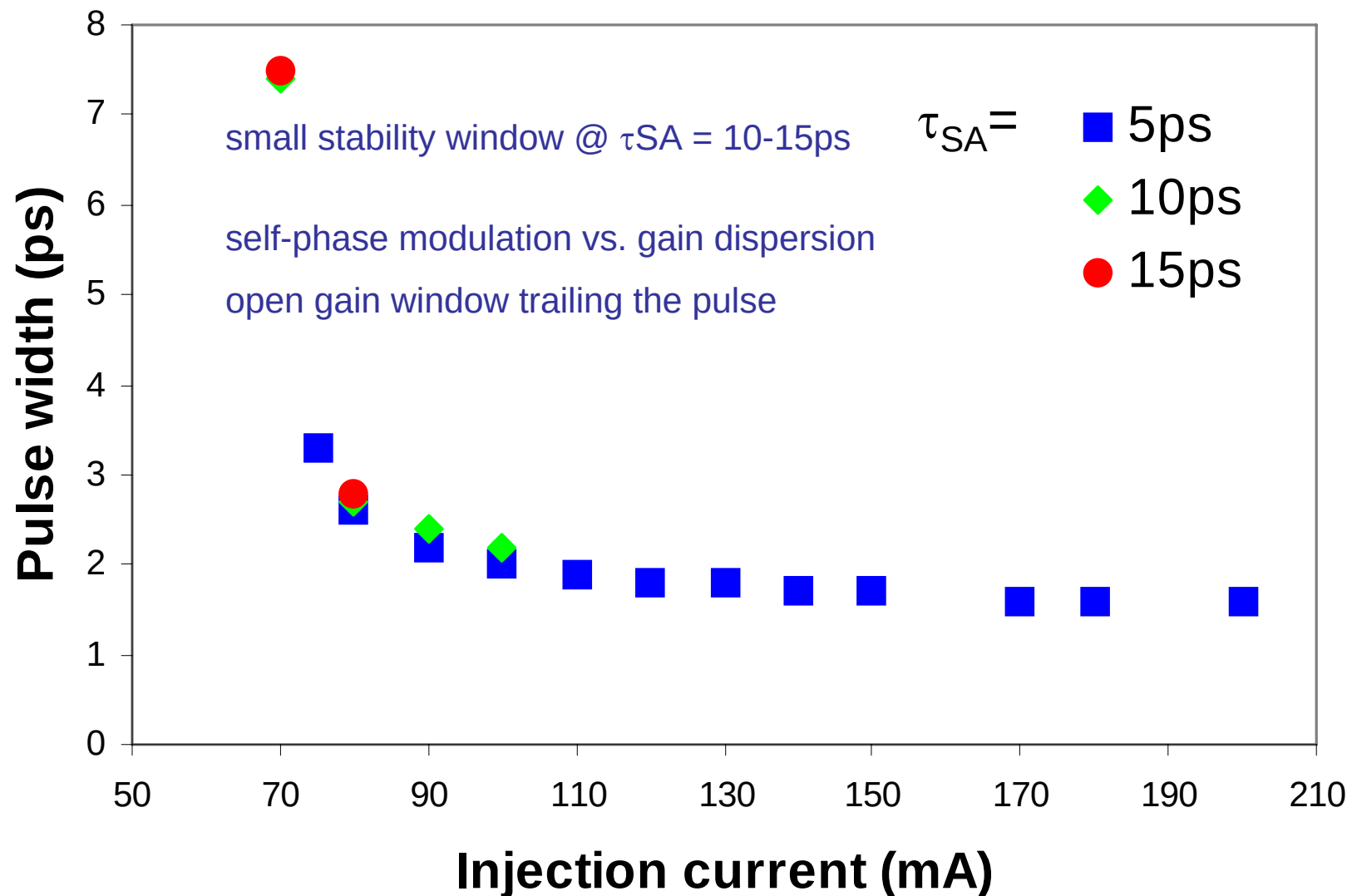
Approximation valid when change per roundtrip is limited

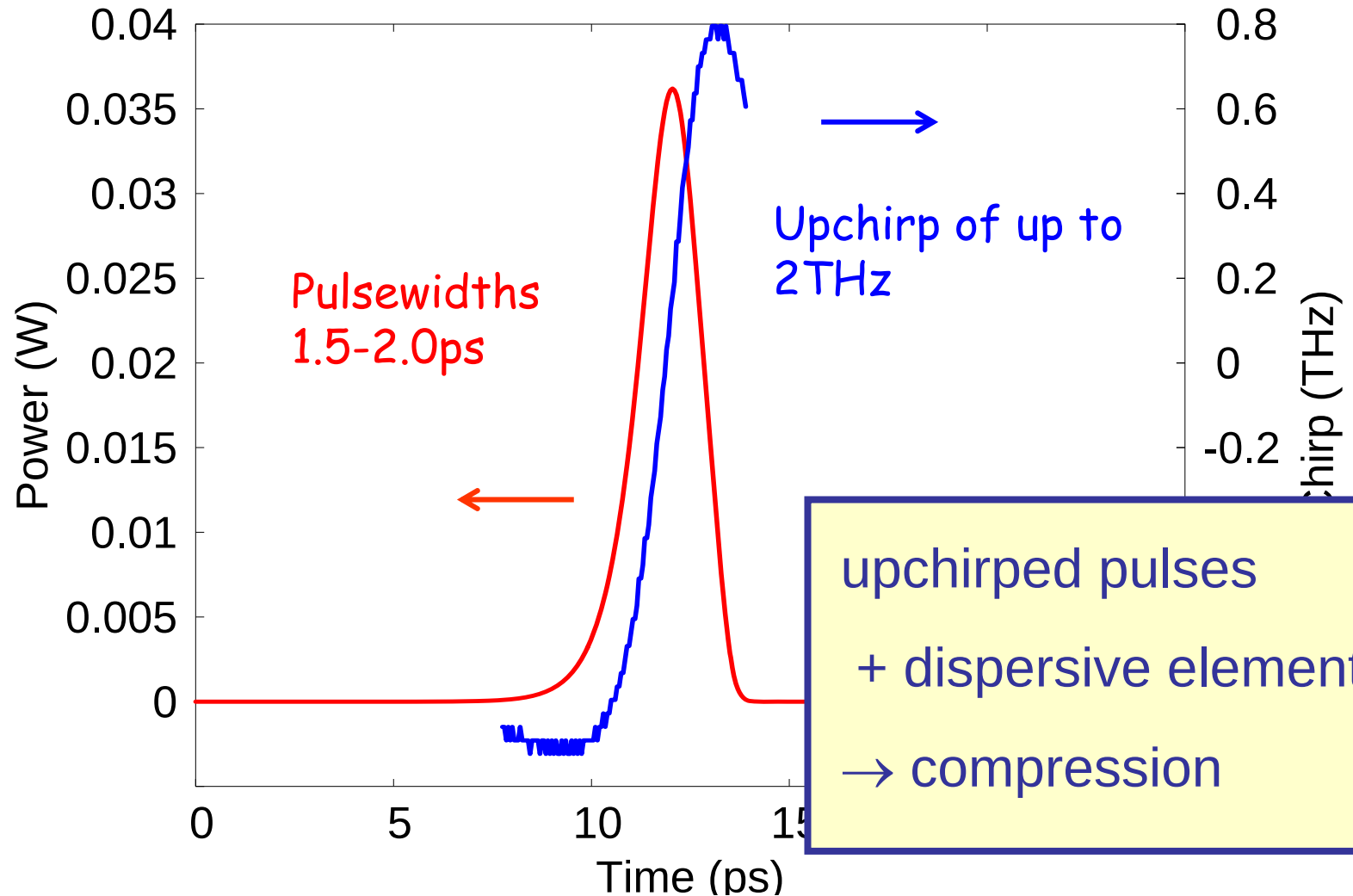
TU/e Modeling the ring laser

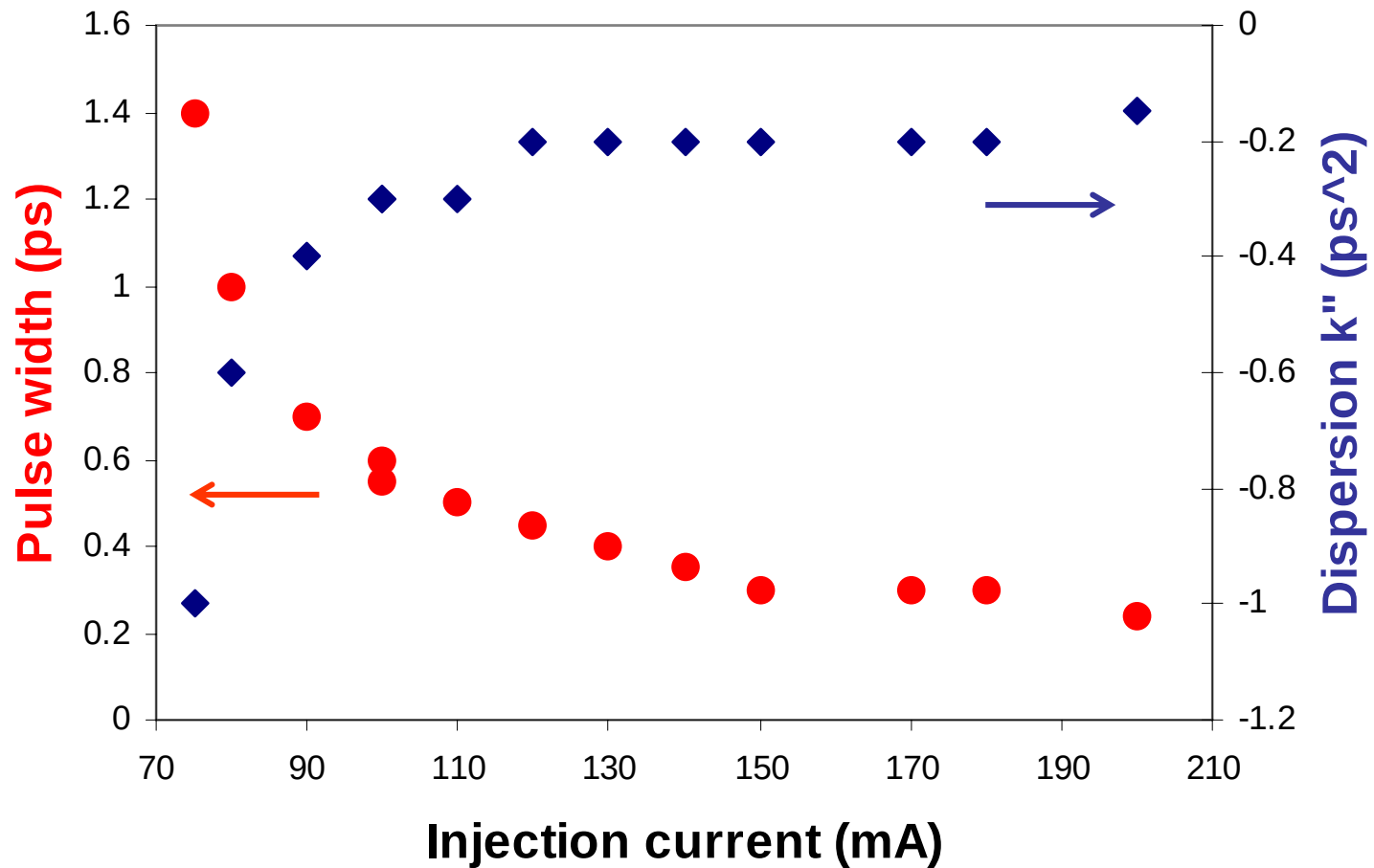
- InP/InGaAsP
- active-passive (Q1.25/Q1.55)
- 40 GHz cavity
- 50% outcoupling
- 30nm system bandwidth



$$k''_{tot}=0.01\text{ps}^2, L_{SOA}=500\mu\text{m}, L_{SA}=50\mu\text{m}, \alpha_N=5, \alpha_T=3$$



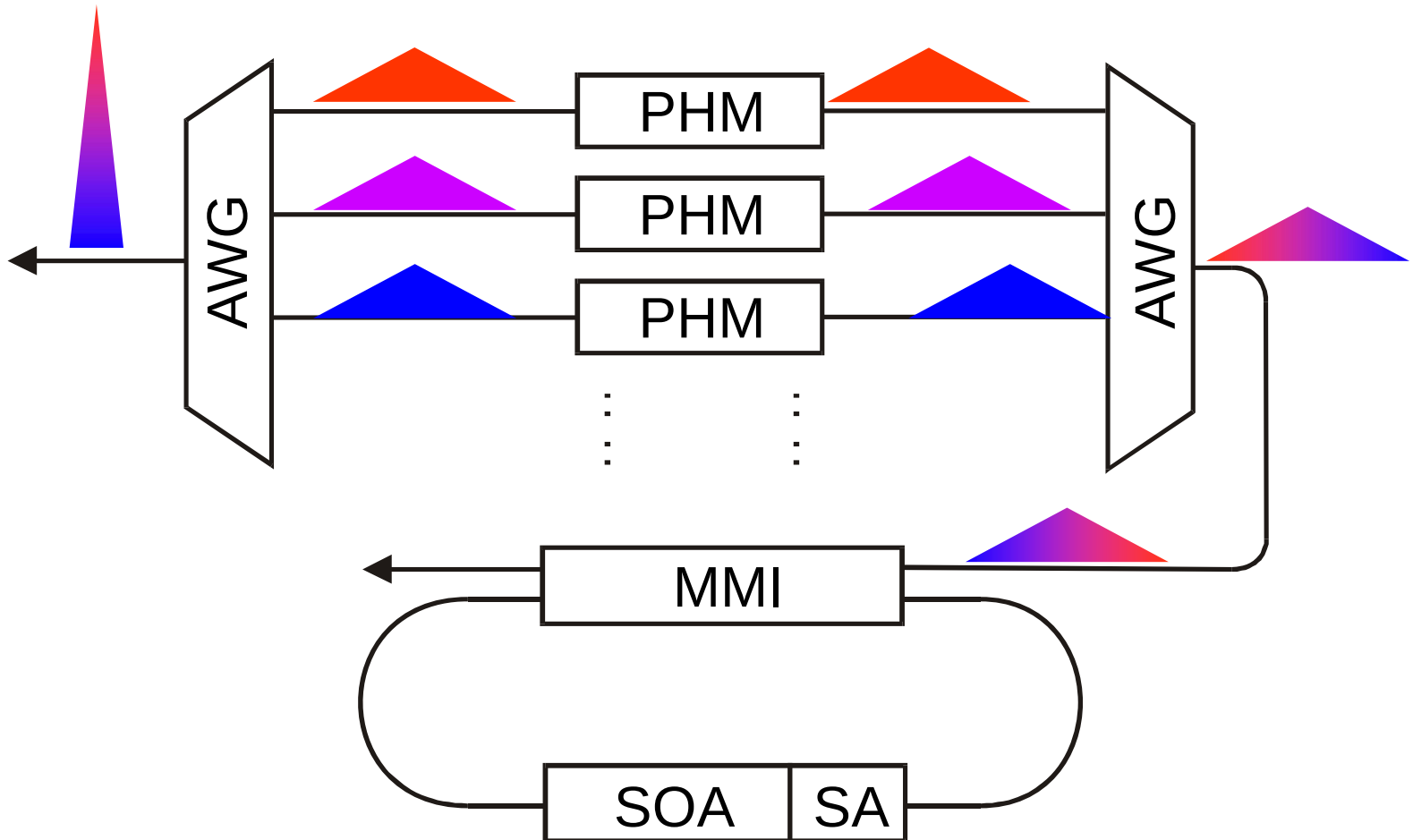


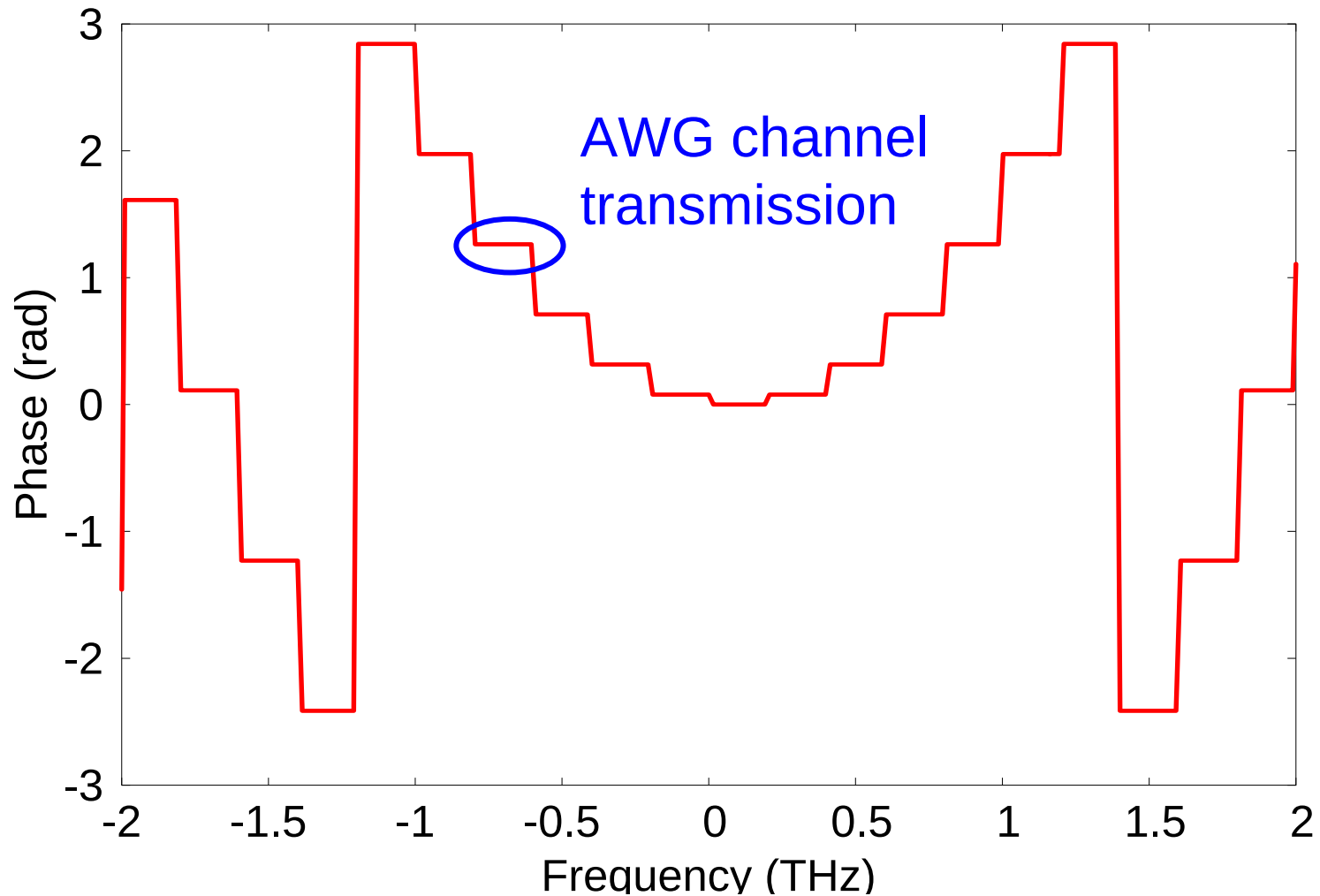


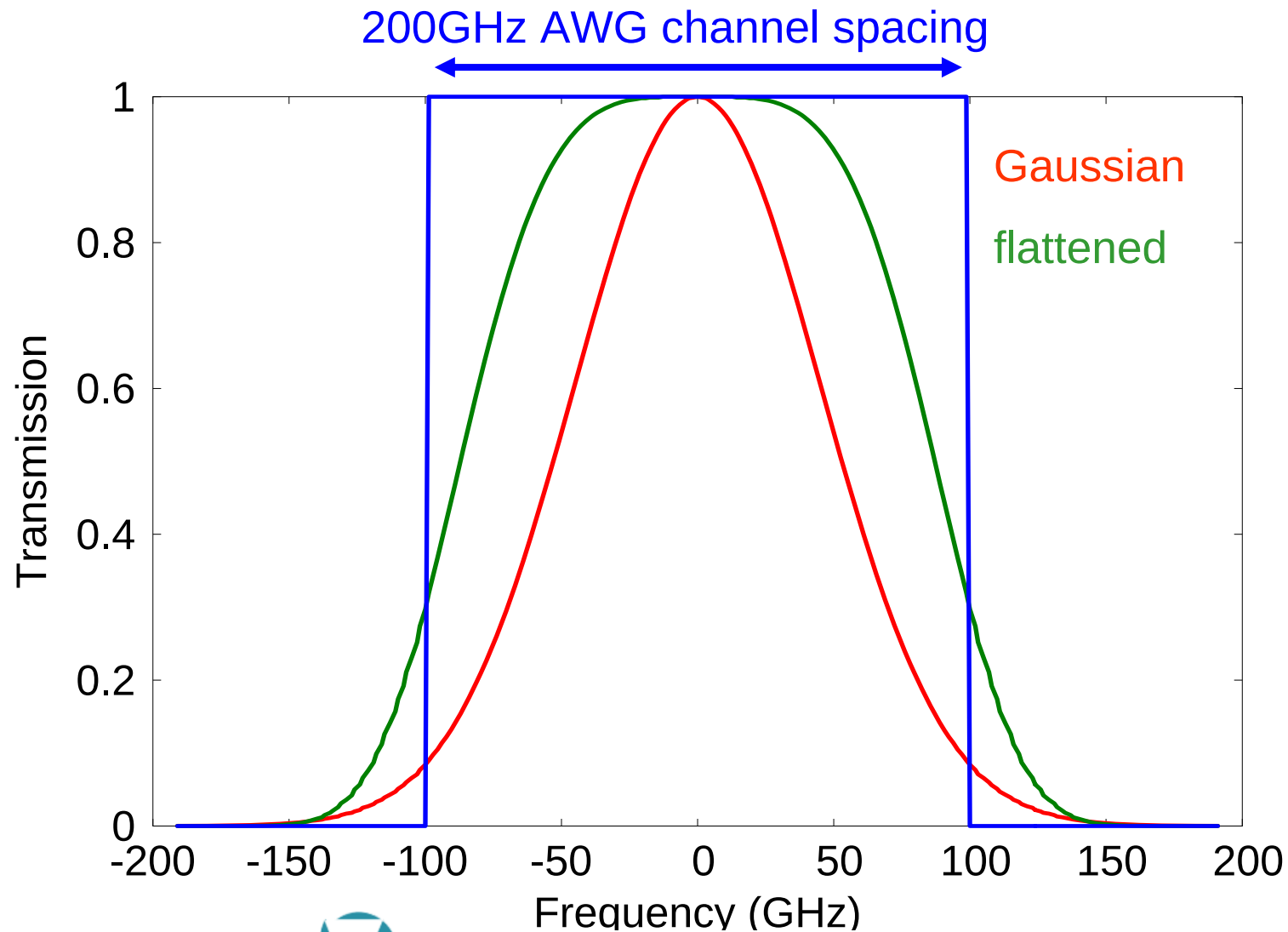
Proposed solutions for Integrated Femtosecond Semiconductor Lasers (IFSL)

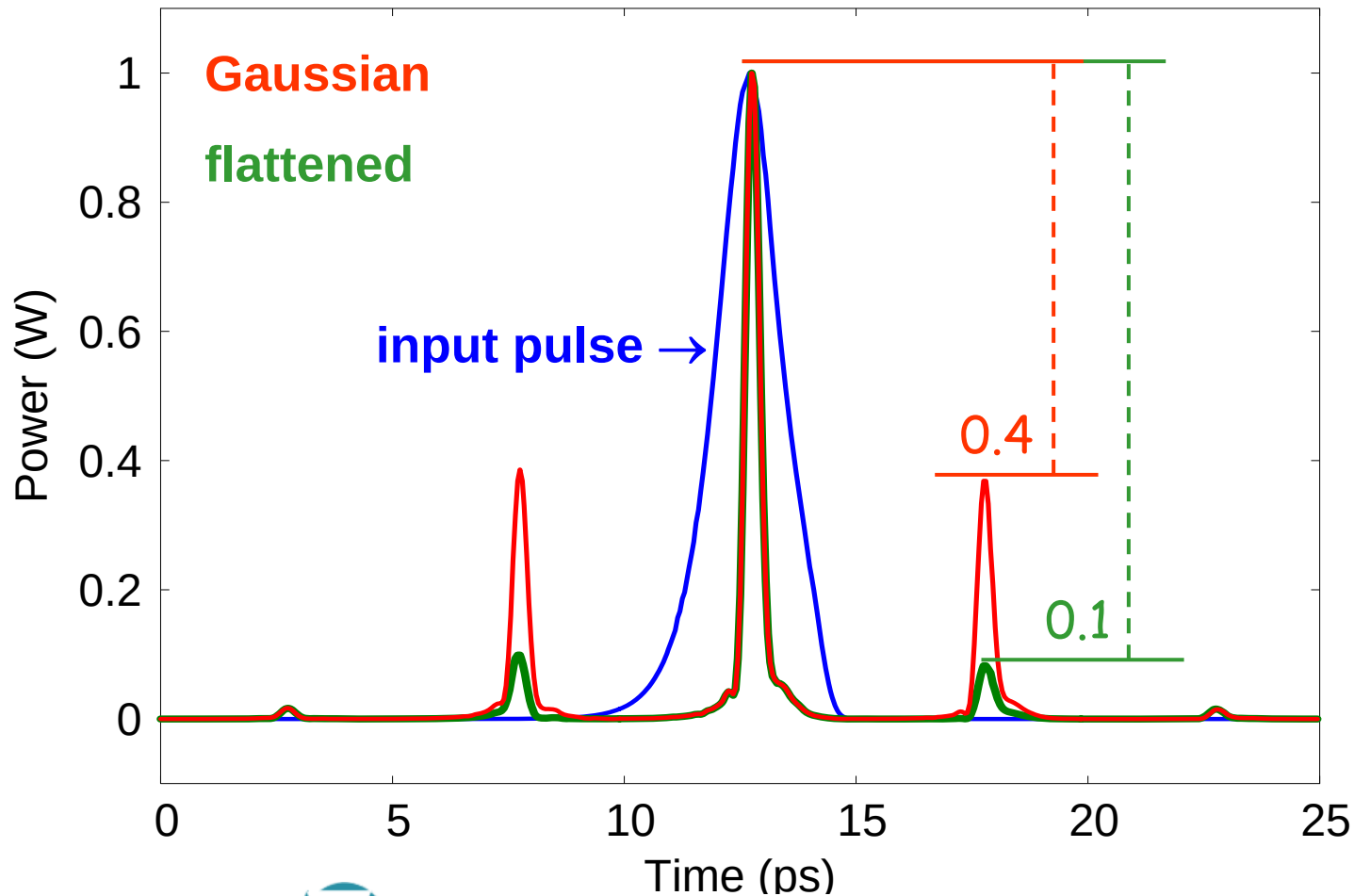
- extracavity pulse compression
- 'breathing mode'

TU/e Pulse compressor

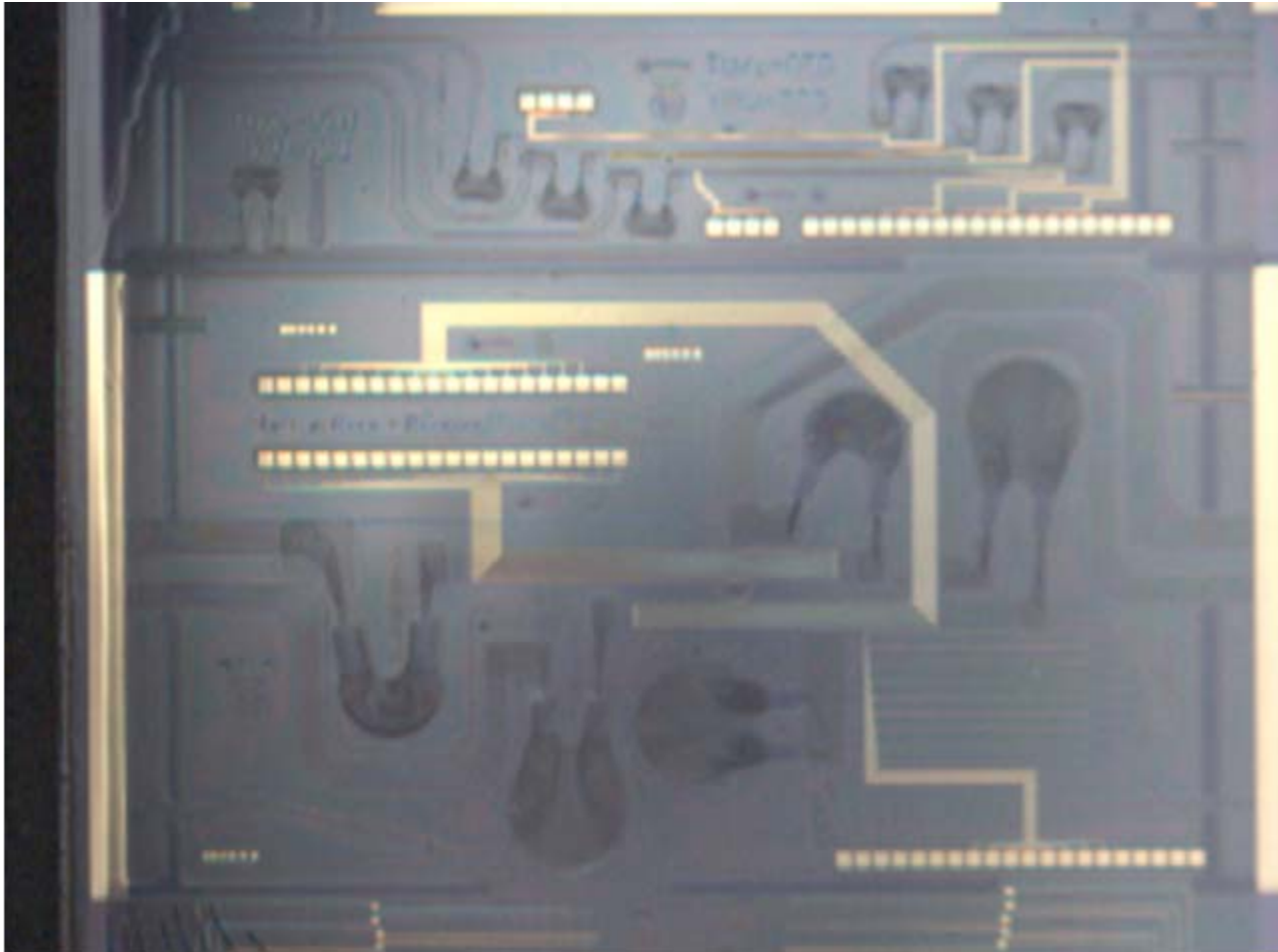






FWHM 1.6ps $\rightarrow$ 300fs

TU/e Realisation of compressor



Martijn Heck – Pascual Munoz (UPVLC - Valencia)



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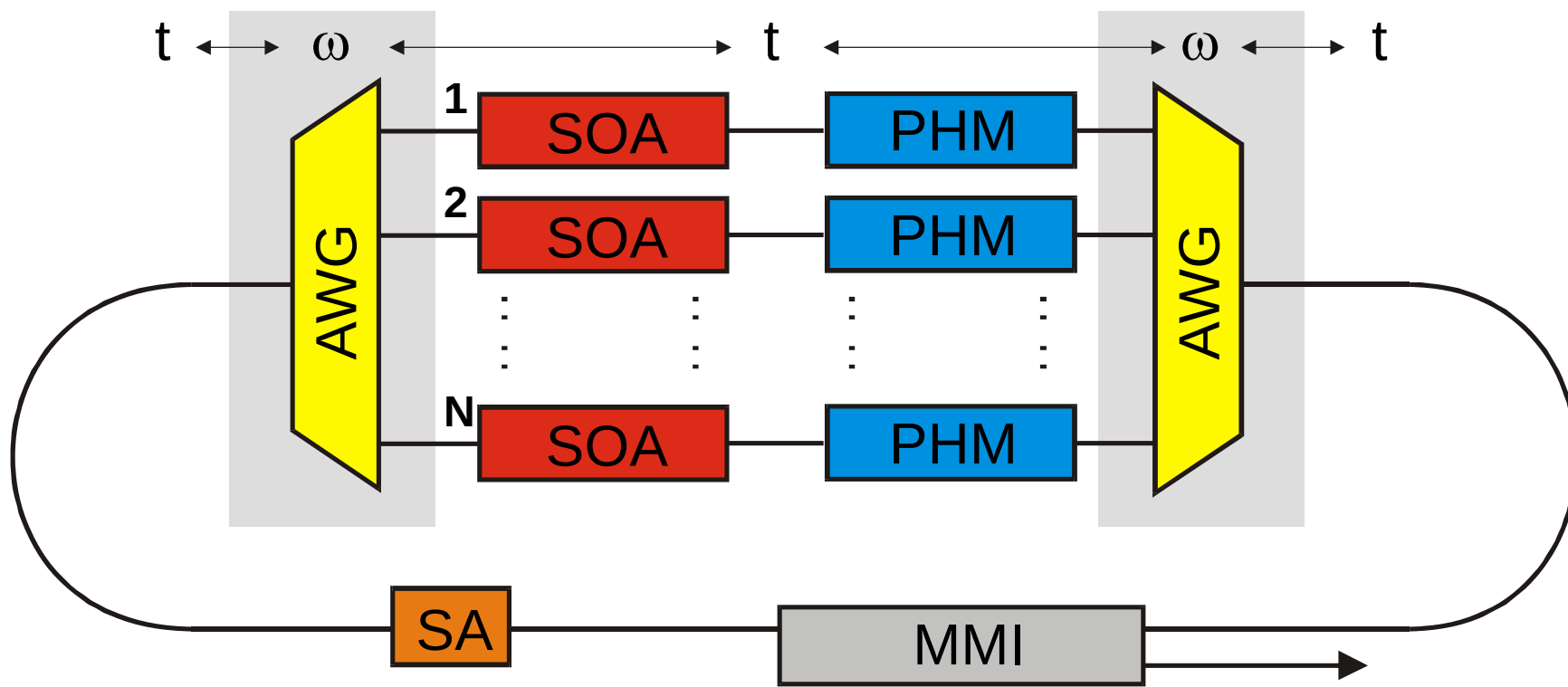


Proposed solutions for Integrated Femtosecond Semiconductor Lasers (IFSL)

- extracavity pulse compression
- **‘breathing mode’**
 - Self-phase modulation $\leftrightarrow$ gain dispersion
 - instabilities
 - minimize SPM!

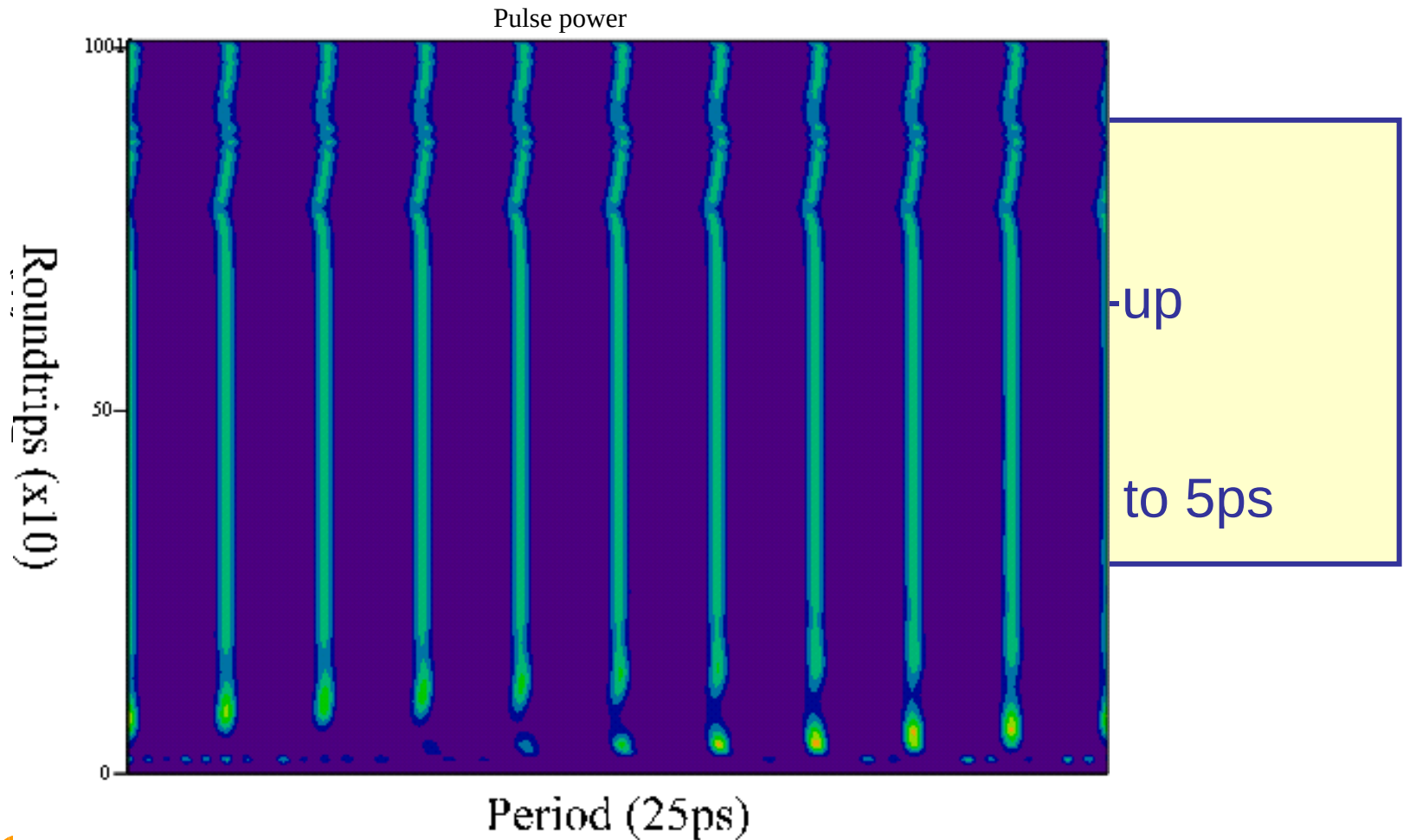
Compensate phase
shift in SOA:
0 to 2π

- Minimizes SPM in SOA
- Dispersive cavity
- Small stability regime

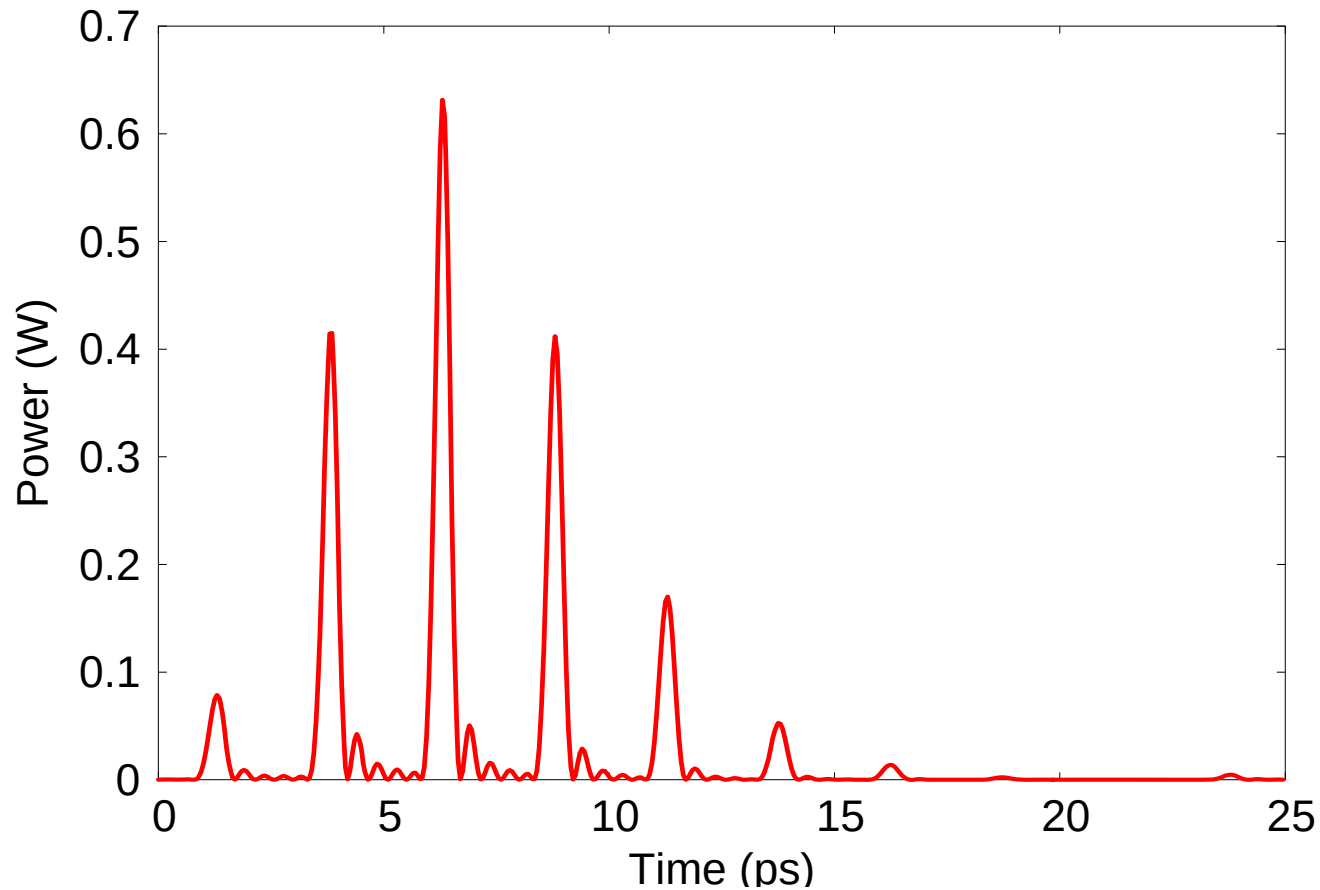


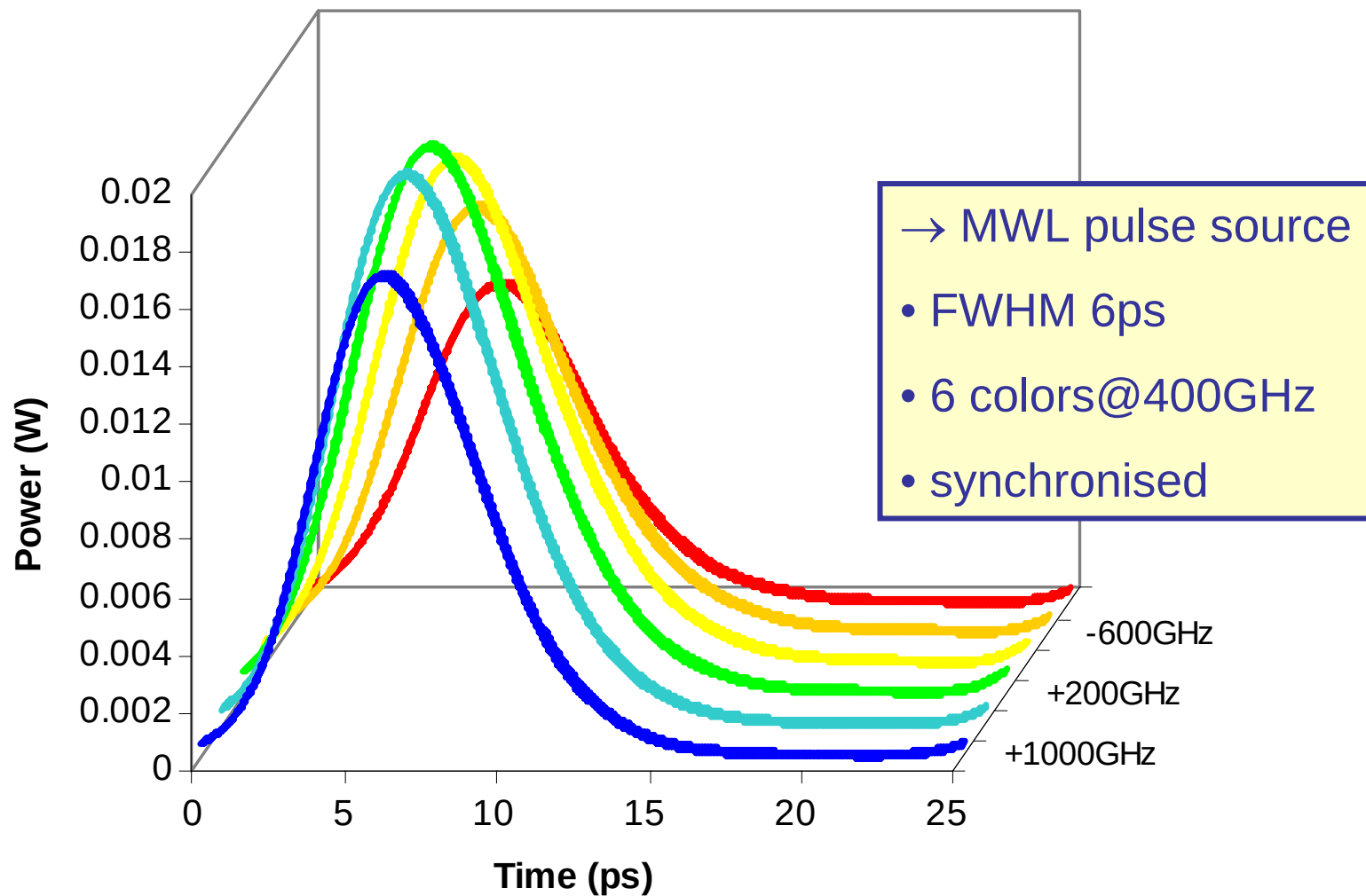
Bandwidth: #channels x channel spacing

6 x 400GHz, $\tau_{\text{abs}}=15\text{ps}$

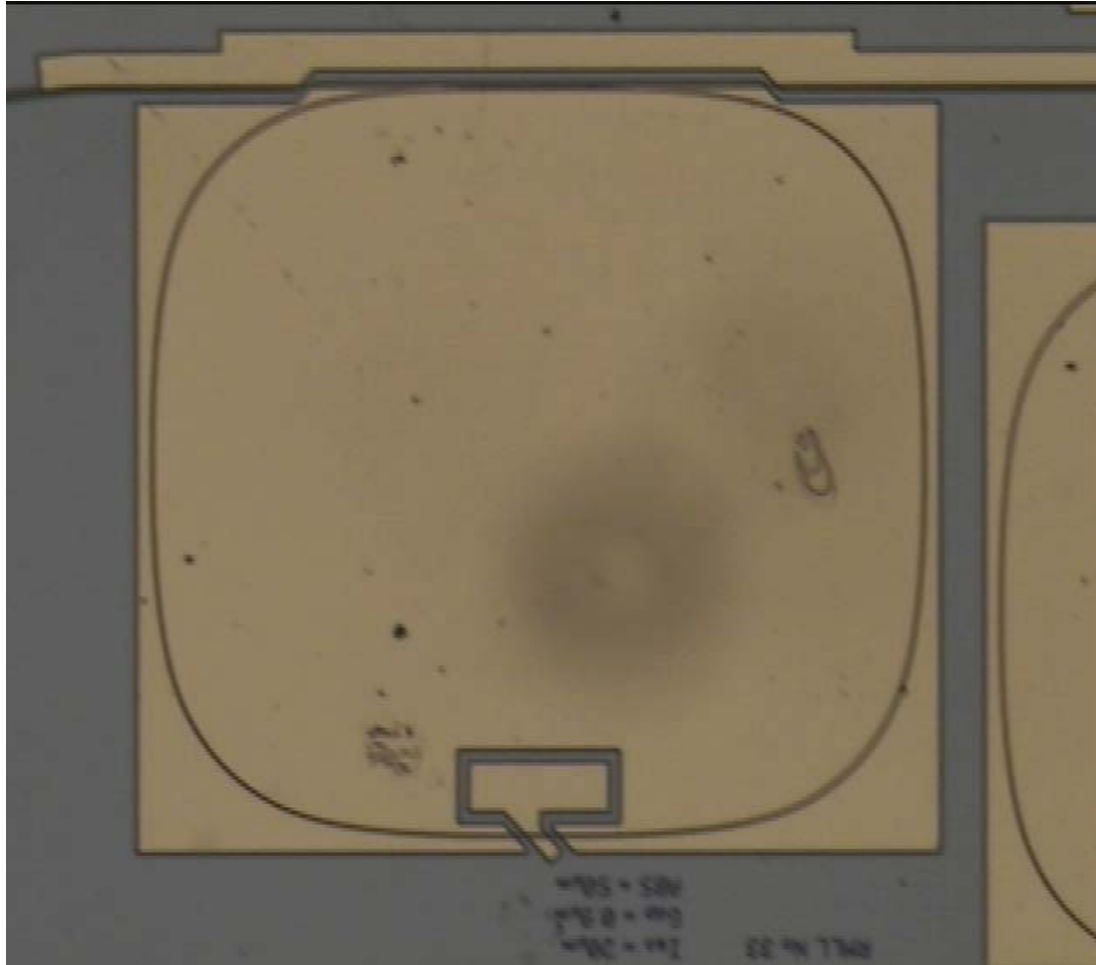


6 x 400GHz, $\tau_{\text{abs}}=5\text{ps}$





TU/e All-active 15GHz Ring MLL



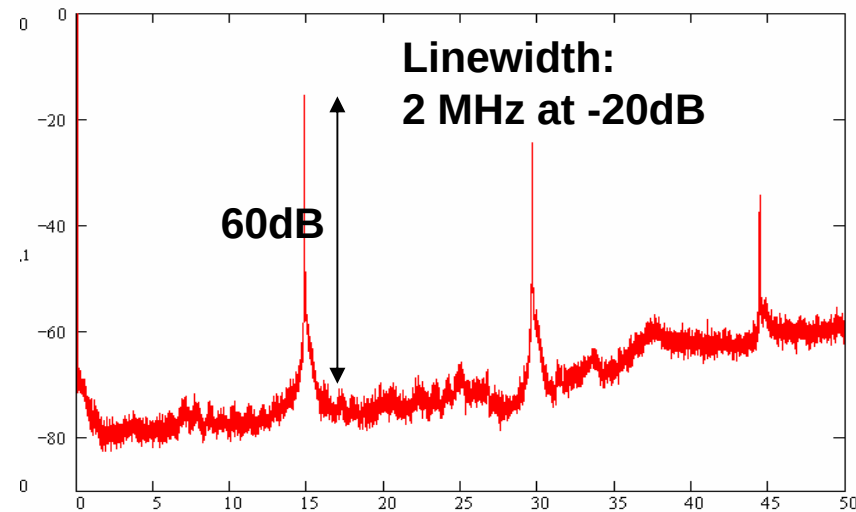
15GHz ring cavity
with adiabatic bends

50 μ m SA

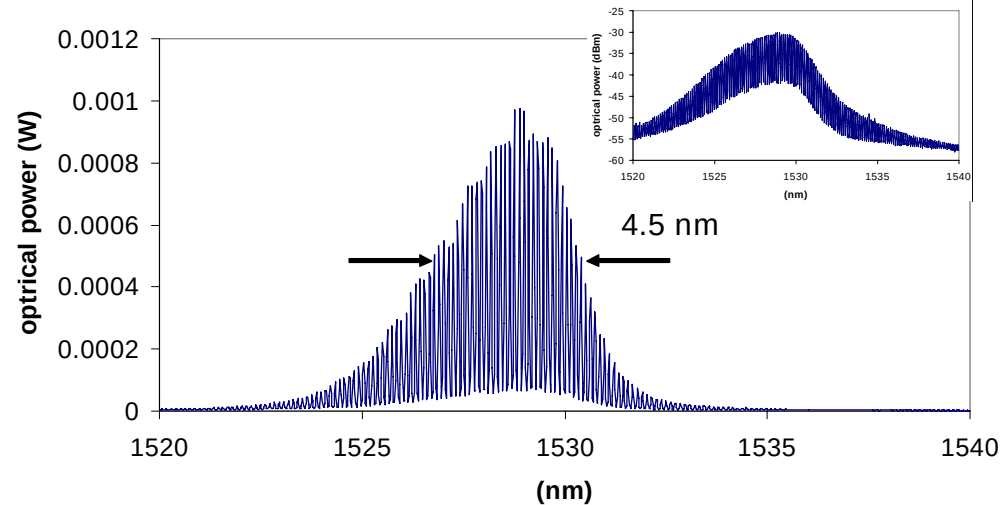
Directional coupler

Angled facet output
+ AR coating

TU/e 15GHz Ring MLL results

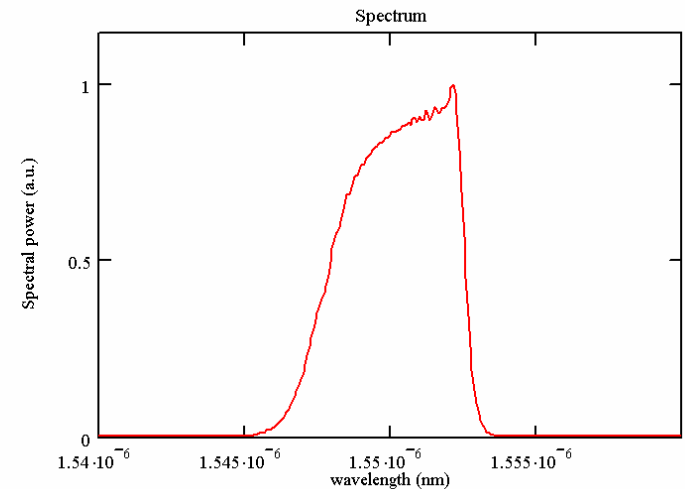
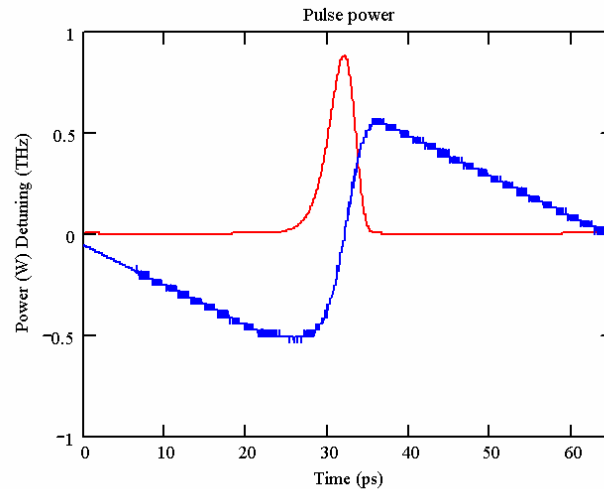


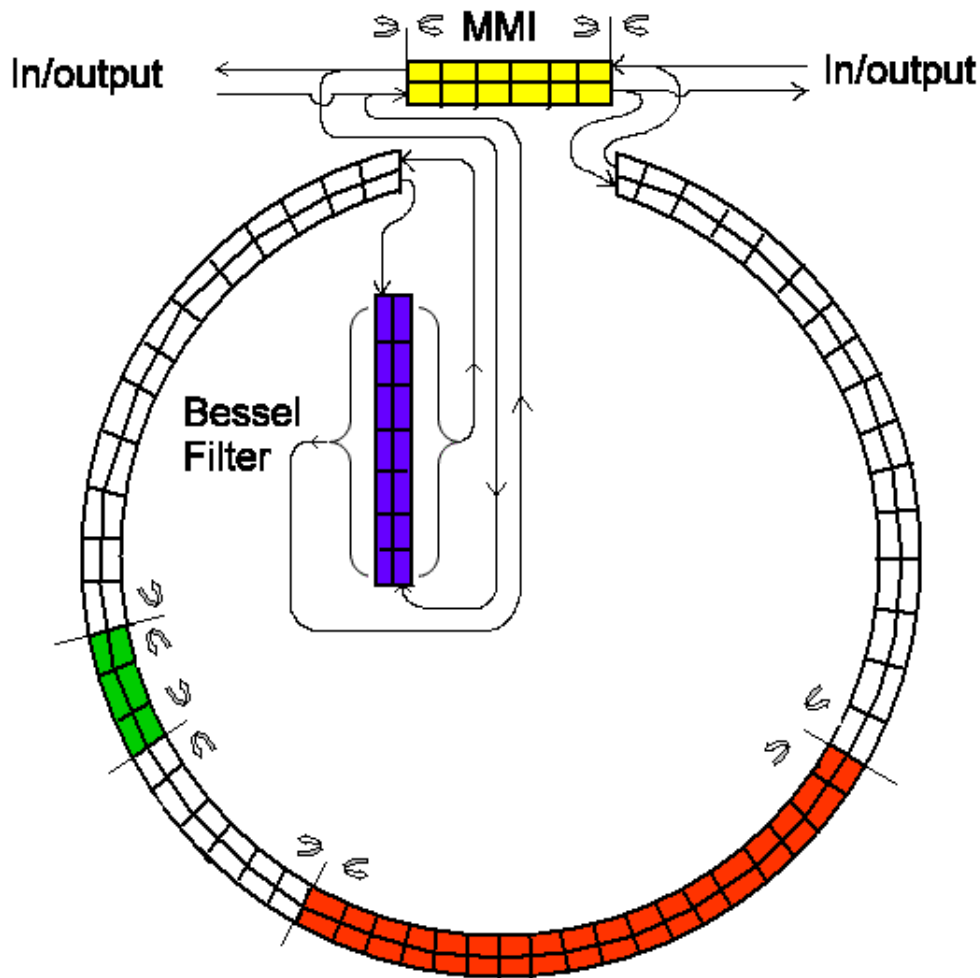
optical spectrum $V=-1.6V$ $I=145mA$



Simulation

3.3 ps pulse width
1.2THz detuning
4.5nm bandwidth





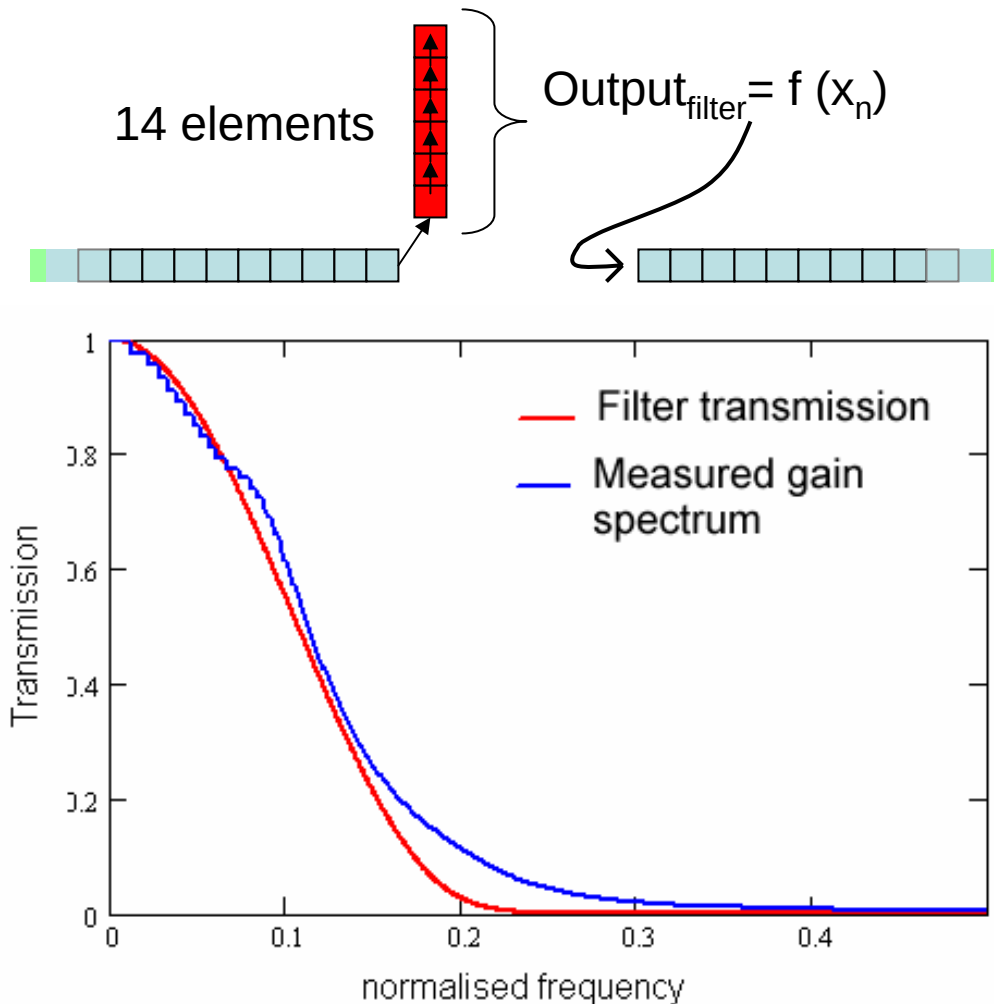
Ring divided in 25 fs segments

- Waveguide
- Amplifier
- Absorber
- MMI coupler
- Filter's register

Reflections
No phase equation
No TPA and gain compression

$$G = \Gamma a_N N_{tr} \ln \left(\frac{N}{N_{tr}} \right)$$

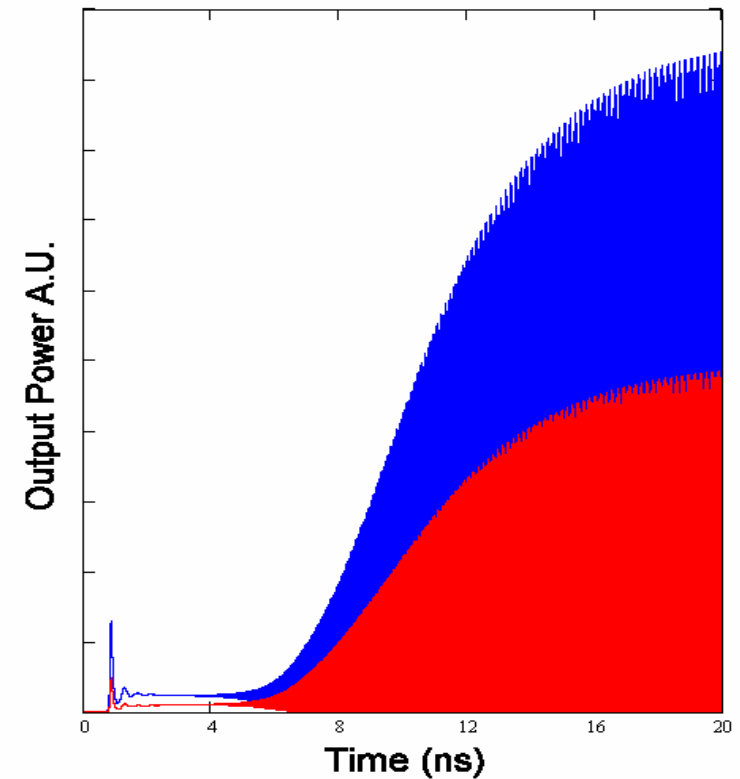
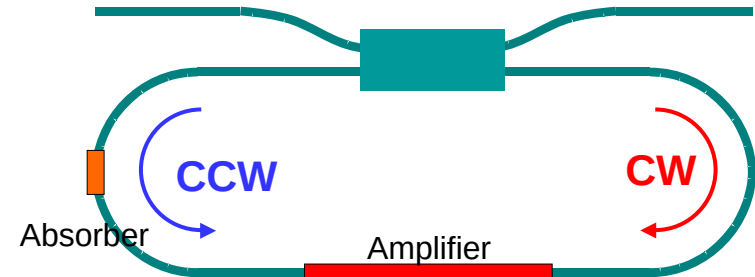
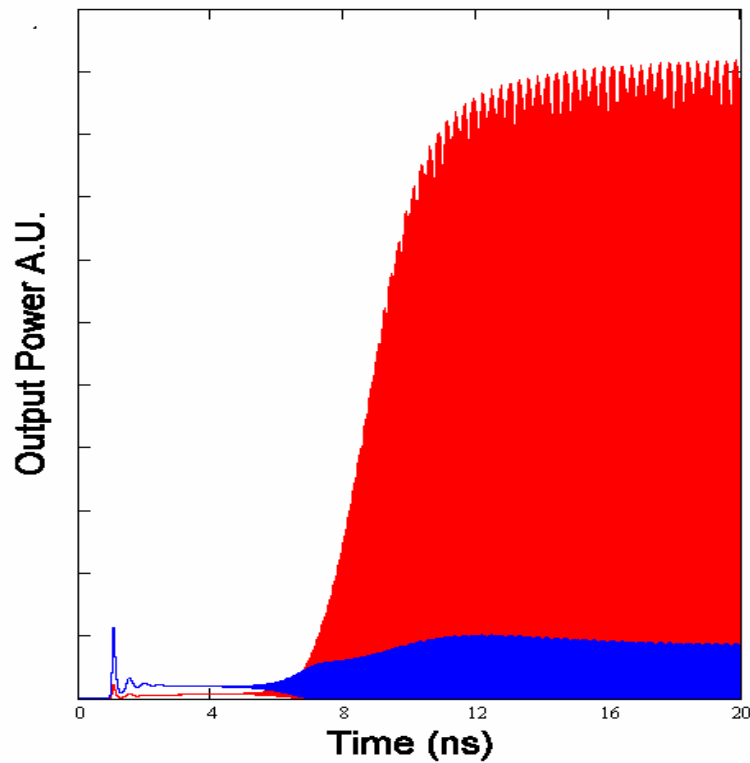
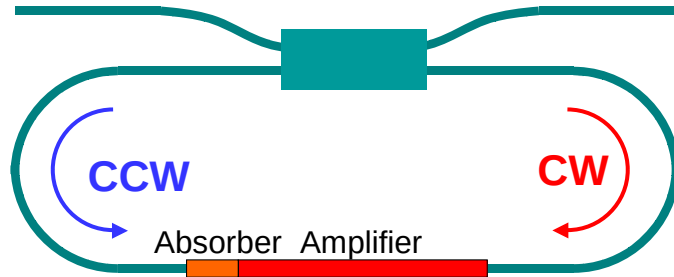
TU/e The spectral bandwidth

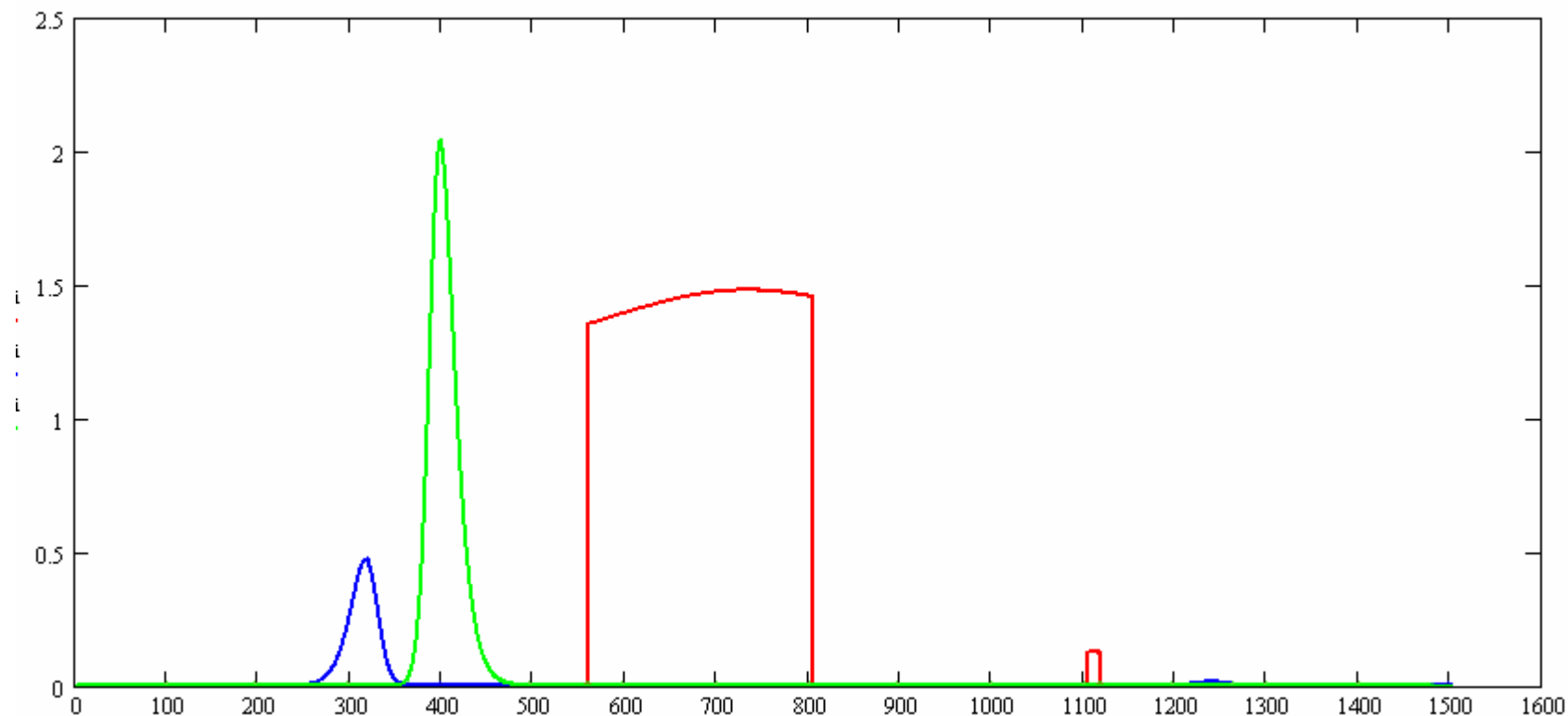
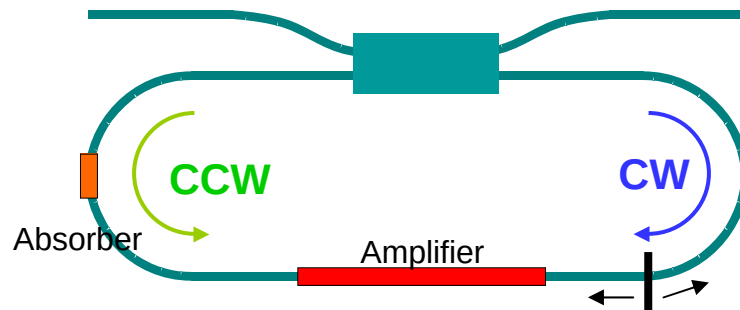


A Bessel digital filter is used:

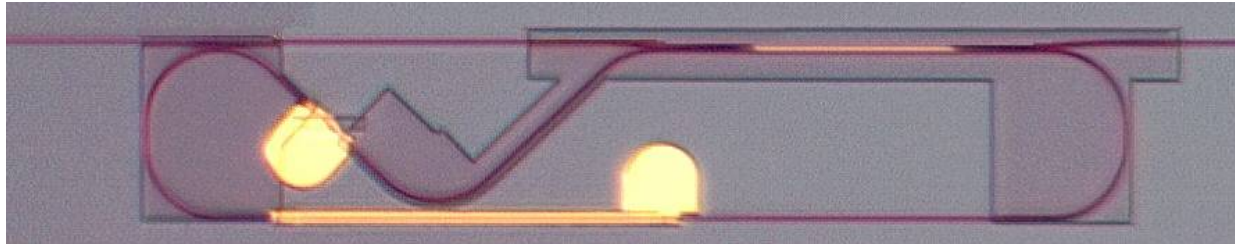
- Numerically stable
- The transmission is similar to the measured SOA gain spectrum.

TU/e Positioning of the absorber

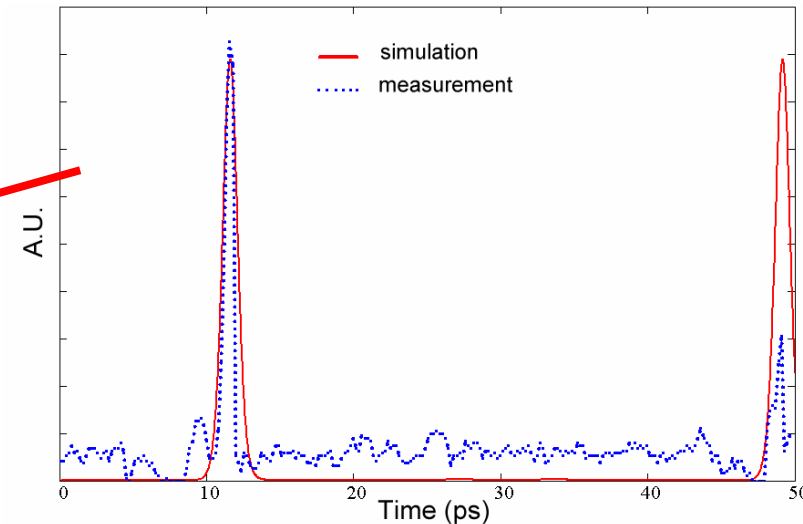
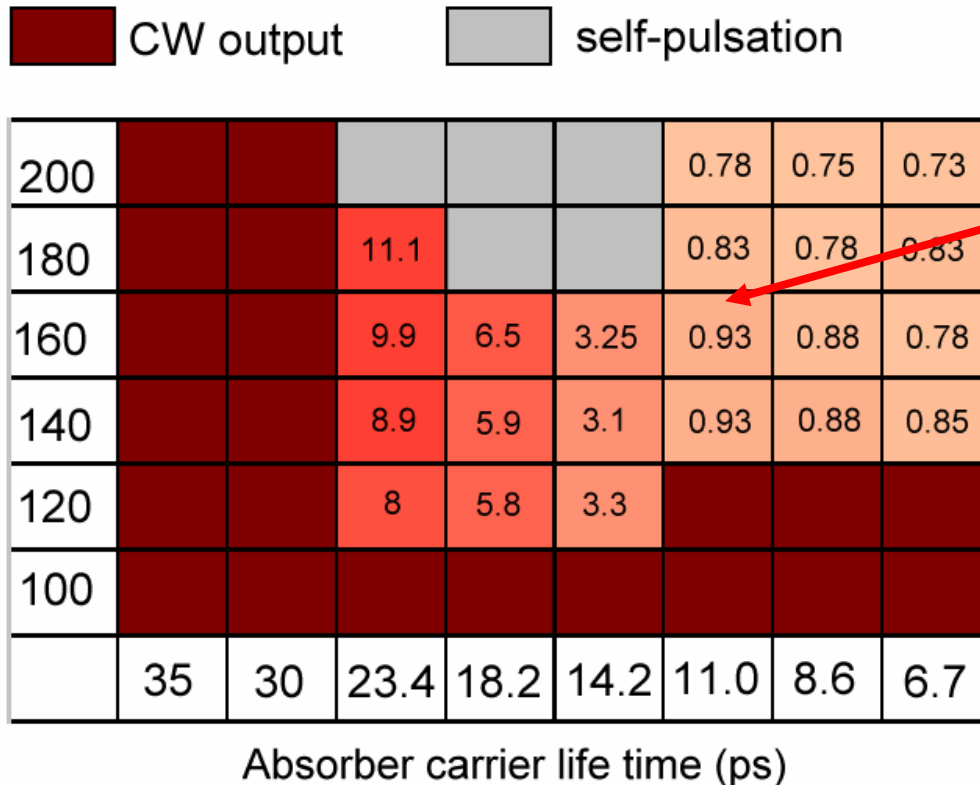




TU/e 26 GHz ring laser result

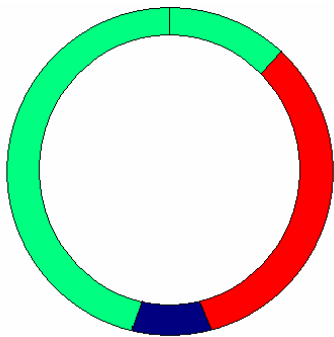


*Modelocked 26GHz ring laser by Y. Barbarin et al.
IEEE PTL, publ. Nov 2005*

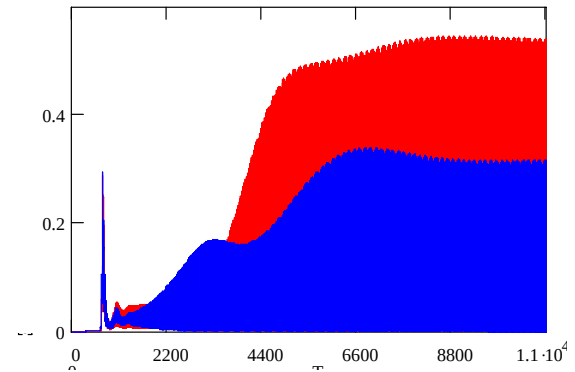


Two directional model

phase equations and nonlinear effects (amp. And abs.)
no intra-cavity reflections

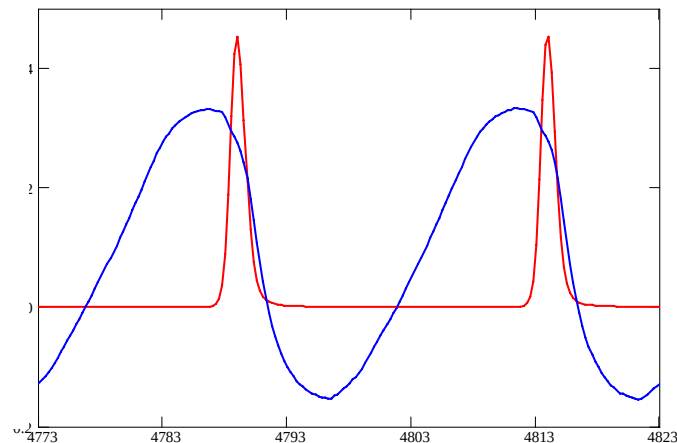


40GHz ring
1000 segments
14th order digital bandwidth filter
700 μm long amplifier
20 μm long SA



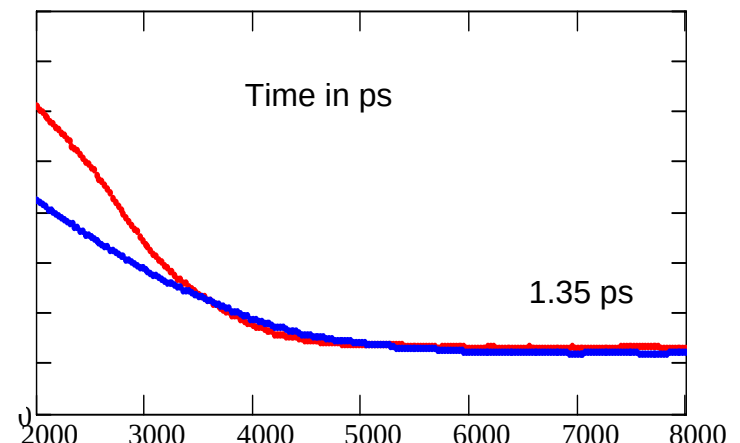
Result for $I_{\text{amp}} = 175\text{mA}$ and $T_{\text{abs}} = 15\text{ps}$

Power and Phase v.s. time



Time in ps

Pulse width v.s. time after start-up



Time in ps

TU/e Conclusions

- Set up simulation tools for designing integrated modelocked lasers
- Simulations point a way to integrated fs laser systems
 - Modelocked laser plus compressor
 - Separate amplification of spectral components
- In a ring the power ratio in the two directions can be controlled through the relative position of the amplifier and absorber
- We have started to use the models:
 - to design laser system
 - to analyse results obtained with devices



