DESY SUMMER STUDENT PROGRAMME 2019

PHOTON SCIENCE, PROF. FRANZ KÄRTNER

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SIMULATION OF A NONLINEAR INTERFEROMETER FOR AN INTEGRATED MODE-LOCKED LASER

https://ufox.cfel.de/sites/sites_cfelgroups/site_cfel-ufox/content/e16281/e35211/e60563/e61551/2018_10_19_NLO_L1_ODM.pdf

MOTIVATION

Goal: produce high-intensity, ultra-short pulses with an integrated laser.

The Nobel Prize in Physics 2018 was awarded

"for groundbreaking inventions in the field of laser physics"

to

1. Arthur Ashkin "for the optical tweezers and their application to biological systems"

2. Gérard Mourou and Donna Strickland "for their method of generating high-intensity, ultra-short optical pulses"

https://www.nobelprize.org/prizes/lists/all-nobel-prizes-in-physics/

What is that useful for?

→ (eye) surgery

→ investigate ultrafast Physics

(‚movies' of molecular dynamics)

→ new properties of materials

→ new ablation techniques

Why integrated?

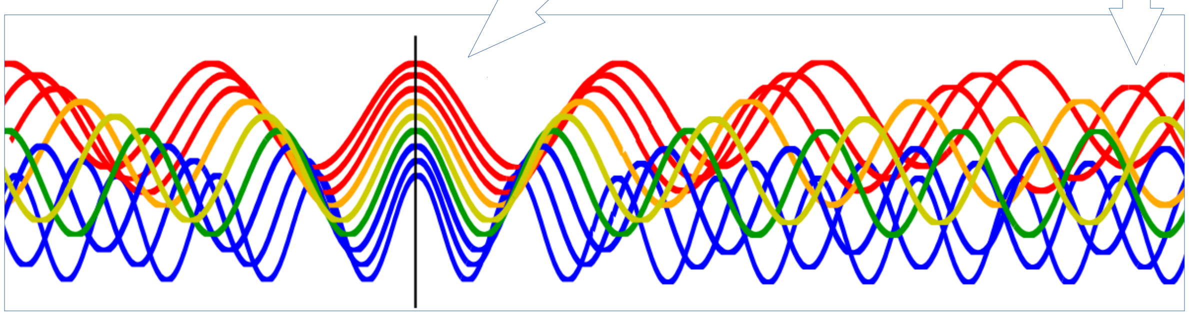
→ application in photonics

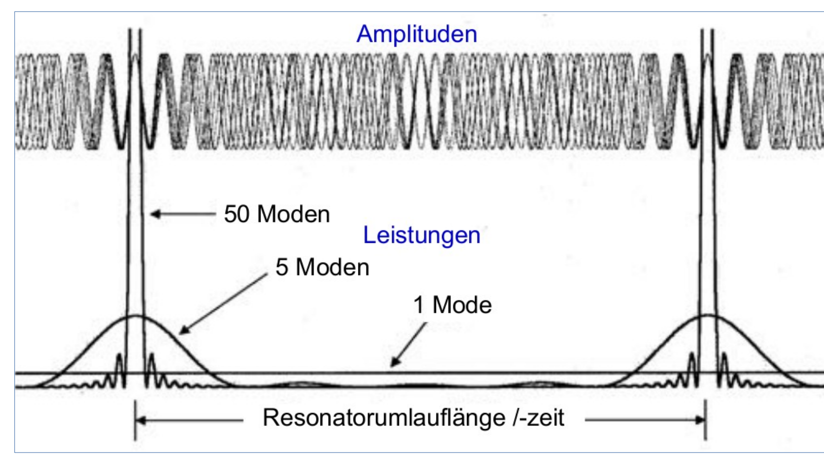
WHAT MEANS MODE-LOCKED?

→ Goal: produce high-intensity, ultrashort pulses with a laser

A so called laser cavity (or resonator) consists in principle just of two mirrors facing each other. By this, we impose boundary conditions on the electromagnetic field inside the cavity → a discrete set of solutions: higher harmonics of base frequency.

→ Now, the main idea is: Use constructive/destructive interference:





Both: script to lecture ‚Physics 6: Atomic & laser physics', UHH, summer semester 17, Prof. Schnabel

PULSE SHAPING EQUATION

Governing equation from Physics :

$$\partial_z u(z,t) = \left(g - l + D_g \partial_t^2 + q(u,z,t)\right) u(z,t) + iD\partial_t^2 u(z,t) - i\gamma |u|^2 u(z,t)$$

The q(u,z,t) depends on the actual method used to modelock.

More general formulation :

$$\partial_z u = \left(c_0 + (c_1 + ic_2)\partial_t^2 + q(u,z,t) + ic_3 |u|^2\right) u$$

Self phase modulation
Nonlinear RHS
sol.: $u(z,t) \approx e^{i\gamma |u_{z_{before}}|^2 z}\, u_{z=0}(t)$
Energy conserving
New frequencies develop
Front gets red-, back blueshifted

gain/loss
solution: $u(z,t) = e^{c_0 z}\, u_{z=0}(t)$
$c_0 > 0$: exponential buildup
$c_0 < 0$: exponential decay

Diffusion, frequency filter
FT: $\partial_z \tilde{u}(z,\omega) = -c_1 \omega^2 \tilde{u}(z,\omega)$
sol.: $\tilde{u}(z,\omega) = e^{-c_1 \omega^2 z}\, \tilde{u}_{z=0}(\omega)$
$c_1 > 0$: low pass filter
$c_1 < 0$: high pass filter

Group velocity dispersion
FT: $\partial_z \tilde{u}(z,\omega) = -ic_2 \omega^2 \tilde{u}(z,\omega)$
sol.: $\tilde{u}(z,\omega) = e^{-ic_2 \omega^2 z}\, \tilde{u}_{z=0}(\omega)$
$c_2 > 0$: low frequencies have higher group velocities
$c_2 < 0$: high frequencies have higher group velocities
Changes temporal shape of u
Energy conserving

One can imagine that this equation applies to a lot of applications.

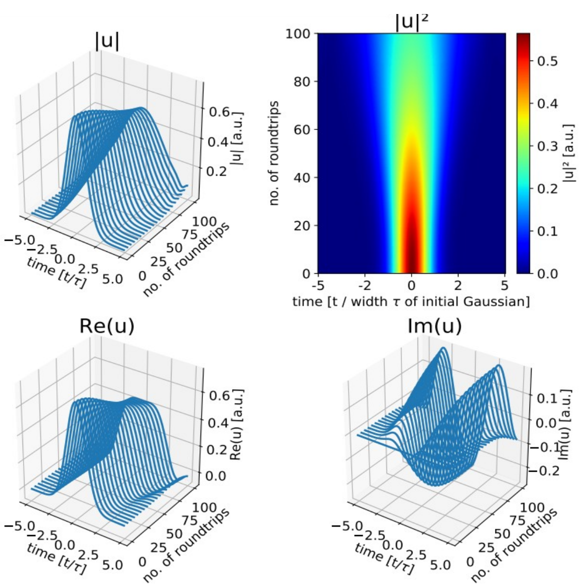
EQUATION USED FOR NLI

In the following :

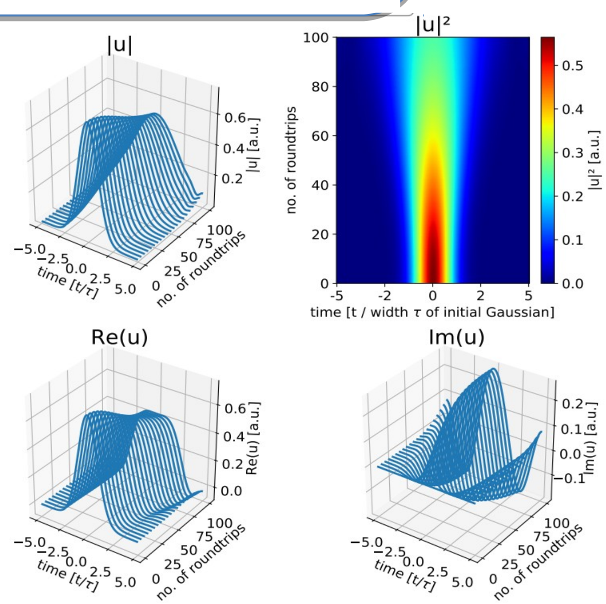
$$\partial_z u(z,t) = iD\partial_t^2 u(z,t) - i\gamma|u|^2 u(z,t)$$

Group velocity dispersion
FT: $\partial_z \tilde{u}(z,\omega) = -iD\omega^2 \tilde{u}(z,\omega)$
sol.: $\tilde{u}(z,\omega) = e^{-iD\omega^2 z}\,\tilde{u}_{z=0}(\omega)$
$D > 0$: low frequencies have higher group velocities
$D < 0$: high frequencies have higher group velocities
Changes temporal shape of u
Energy conserving

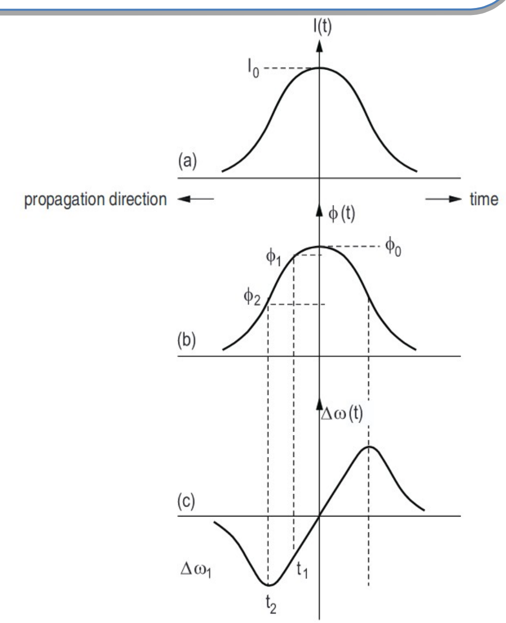
Self phase modulation
Nonlinear RHS
sol.: $u(z,t) \approx e^{i\gamma|u_{z_{before}}|^2 z}\, u_{z=0}(t)$
Energy conserving
Changes spectrum: new frequencies
Front gets red-, back blueshifted



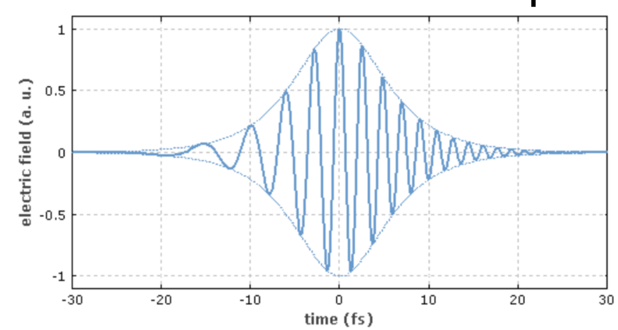
Negative GVD



Positive GVD



SPM leads to a chirp:



https://www.rp-photonics.com/chirp.html

https://ufox.cfel.de/teaching/archive/winter_semester_2015_2016/

SPLIT-STEP FOURIER METHOD

Only GVD and SPM:

$$\partial_z\, u(z,t) = iD\partial_t^2\, u(z,t) - i\gamma|u|^2\, u(z,t)$$

Solve with SSFM:

$$\textbf{function}\ \ u = \mathrm{SSFM}_{fwdEuler}(u_0, N, L, \omega)$$

$$\Delta z = L/N$$

$$u^{(1)} = u_0$$

$$\text{for } n = 1 : N$$

$$\textbf{do}\ \begin{cases} u^{\left(n+\frac{1}{2}\right)} &= \mathfrak{F}^{-1}\left(\mathfrak{F}\left(u^{(n)}\right)\ e^{-i\frac{\Delta z}{2}\,D\,\omega^2}\right) \\ u^{\left(n+\frac{1}{2}\right)} &= u^{\left(n+\frac{1}{2}\right)}\ e^{-i\Delta z\gamma|u^{(n)}|^2} \\ u^{(n+1)} &= \mathfrak{F}^{-1}\left(\mathfrak{F}\left(u^{\left(n+\frac{1}{2}\right)}\right)\ e^{-i\frac{\Delta z}{2}\,D\,\omega^2}\right) \\ u^{(n)} &= u^{(n+1)} \end{cases}$$

$$\textbf{return}\ \ u^{(n)}$$

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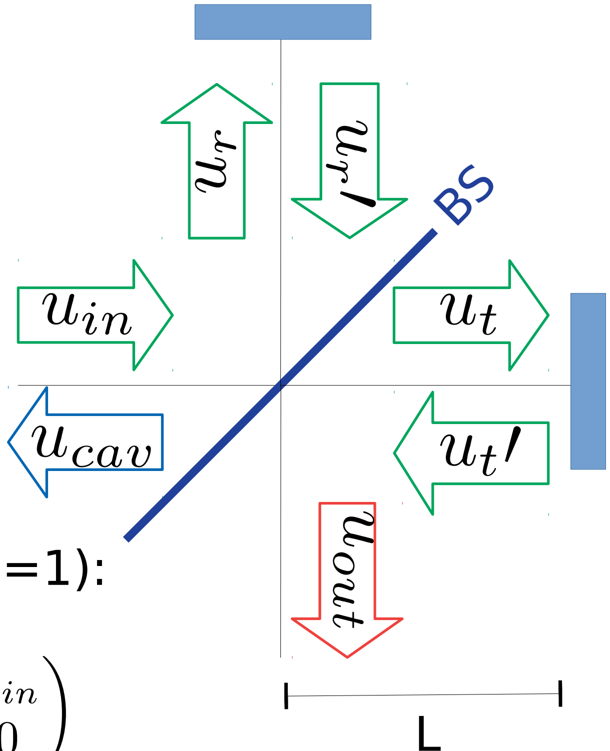
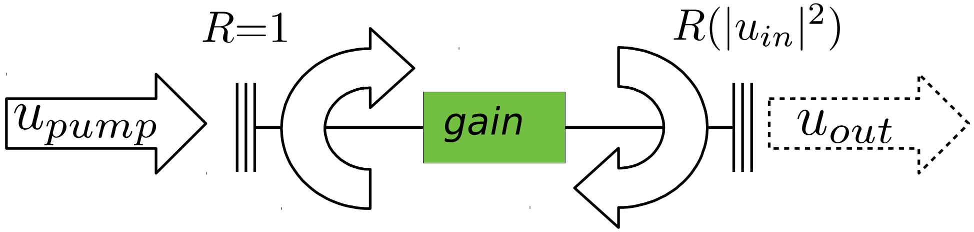
NONLINEAR INTERFEROMETER



General idea for mode-locking: clever loss management.

Here: use a nonlinear interferometer to reflect only high intensity pulses back to the cavity.



Reminder: describe BS by unitary transfer matrix (|det(A)|=1):

$$\begin{pmatrix} u_r \\ u_t \end{pmatrix} = \begin{pmatrix} r_{11}e^{i\phi_{11}} & t_{12}e^{i\phi_{12}} \\ t_{21}e^{i\phi_{21}} & r_{22}e^{i\phi_{22}} \end{pmatrix} \begin{pmatrix} u_{in} \\ 0 \end{pmatrix} \overset{here}{=} \begin{pmatrix} \sqrt{\alpha} & i\sqrt{1-\alpha} \\ i\sqrt{1-\alpha} & \sqrt{\alpha} \end{pmatrix} \begin{pmatrix} u_{in} \\ 0 \end{pmatrix}$$

Now, propagate the input field via transfer matrix:

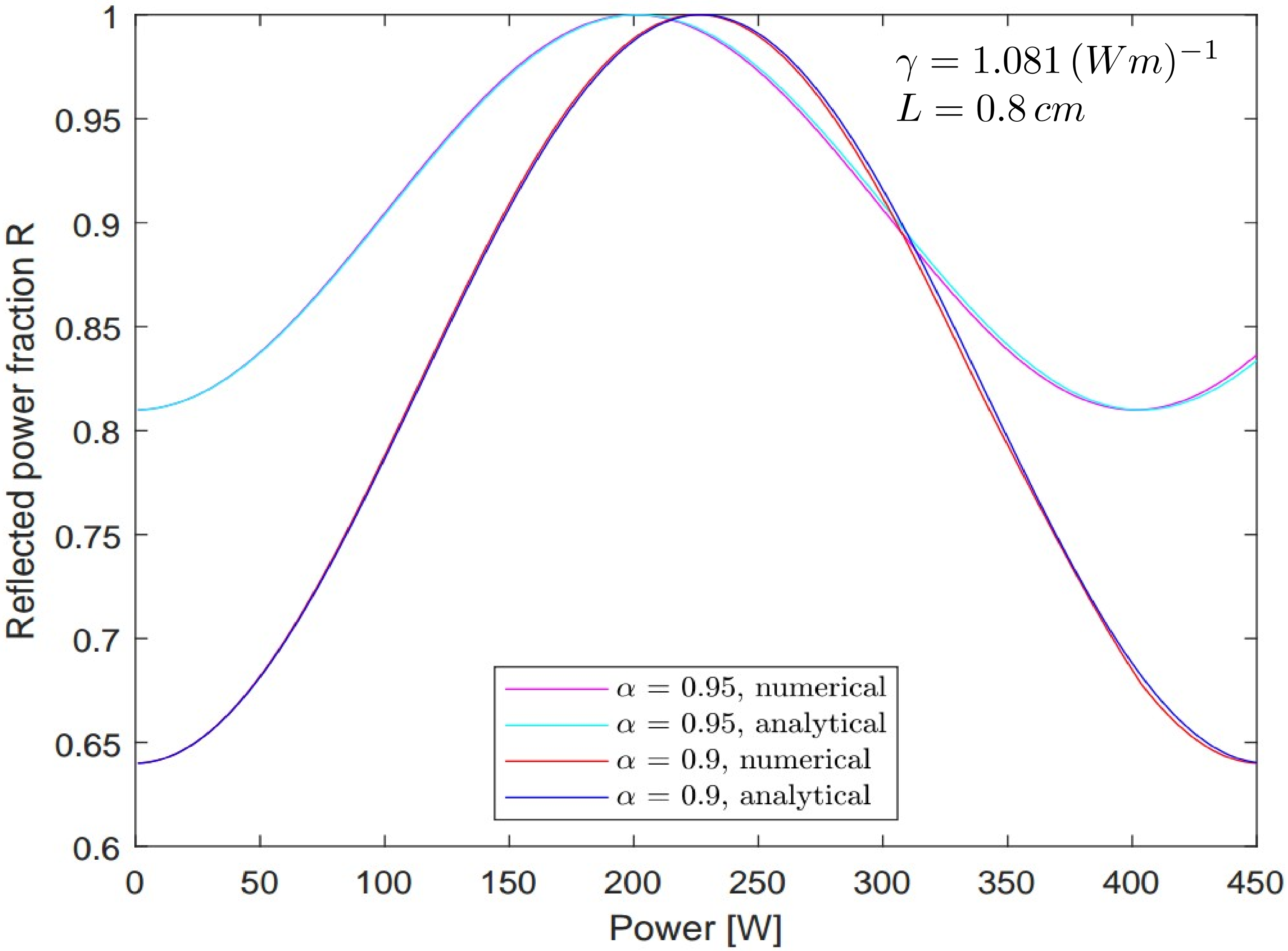
$$\begin{pmatrix} u_{cav} \\ u_{out} \end{pmatrix} = \begin{pmatrix} \sqrt{\alpha} & i\sqrt{1-\alpha} \\ i\sqrt{1-\alpha} & \sqrt{\alpha} \end{pmatrix} \begin{pmatrix} u_r' \\ u_t' \end{pmatrix}, \quad \begin{pmatrix} u_r' \\ u_t' \end{pmatrix} = \begin{pmatrix} u_r \exp\{i\phi_0 + i\gamma|u_r|^2 2L\} \\ u_t \exp\{i\phi_0 + i\gamma|u_t|^2 2L\} \end{pmatrix}$$

Intensity fraction that goes back to the cavity:

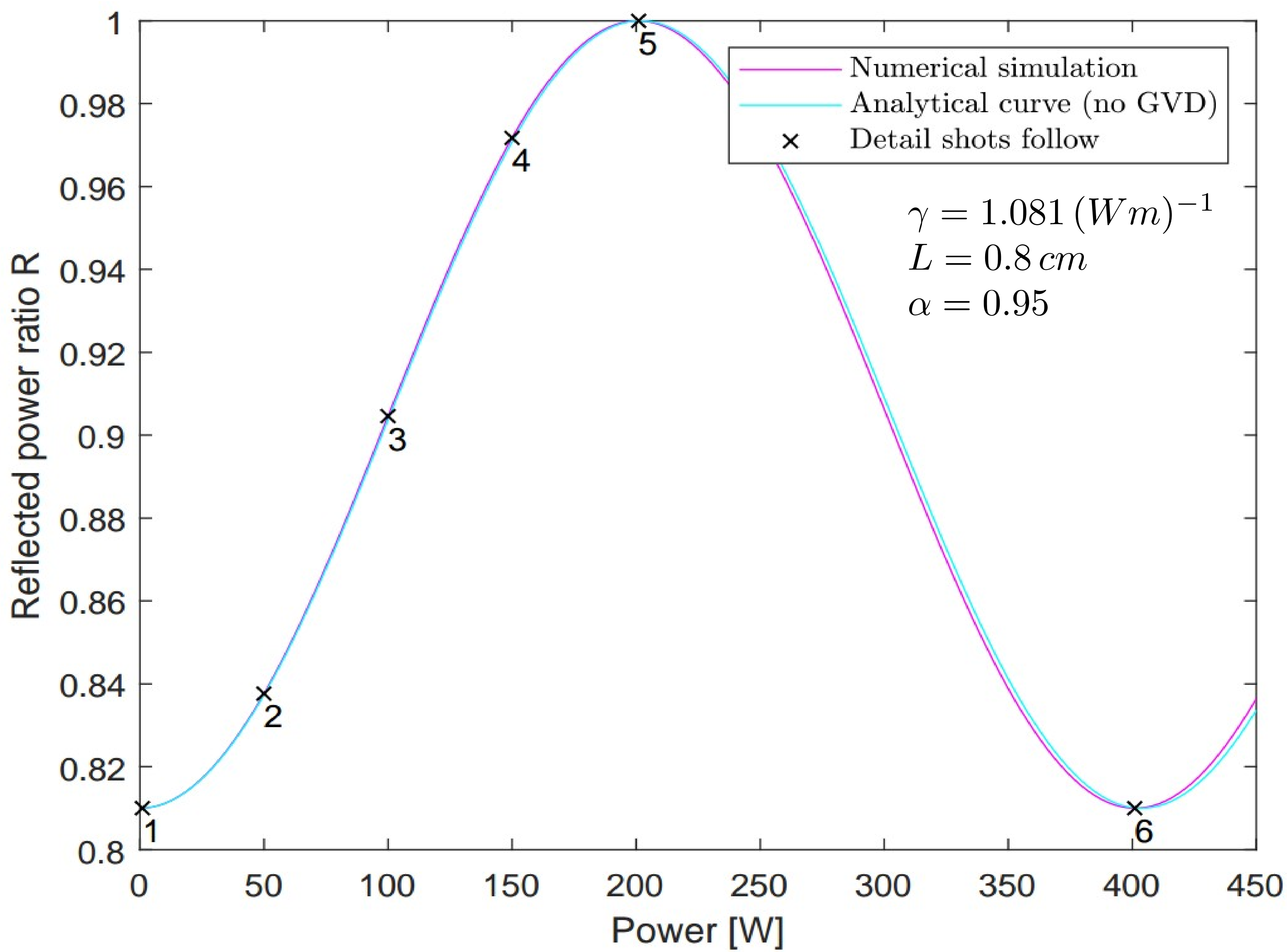
$$R = \frac{|u_{cav}|^2}{|u_{in}|^2} = 1 - 2\alpha\,(1-\alpha)\left\{1 + \cos\left(\gamma\,(1-2\alpha)\,|u_{in}|^2 L\,\right)\right\}$$

REFLECTION CURVES

$$R = 1 - 2\alpha\,(1-\alpha)\left\{1 + \cos\left(\gamma\,(1-2\alpha)\,|u_{in}|^2 L\,\right)\right\}$$

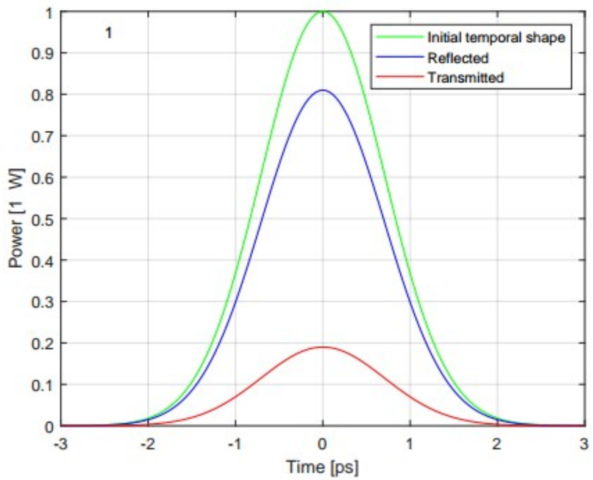


REFLECTION CURVE WITHOUT GVD

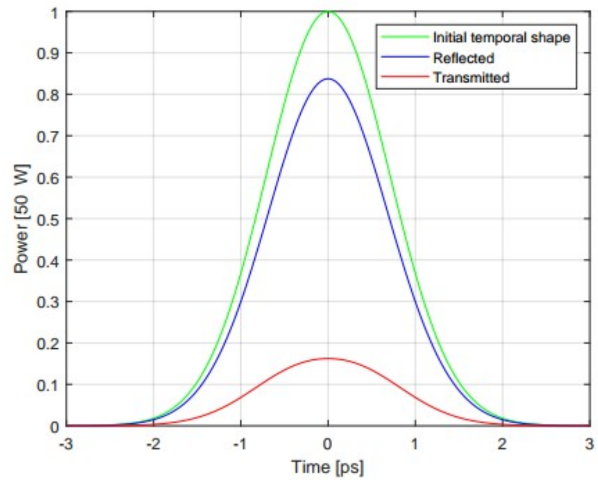


TEMPORAL DETAIL SHOTS

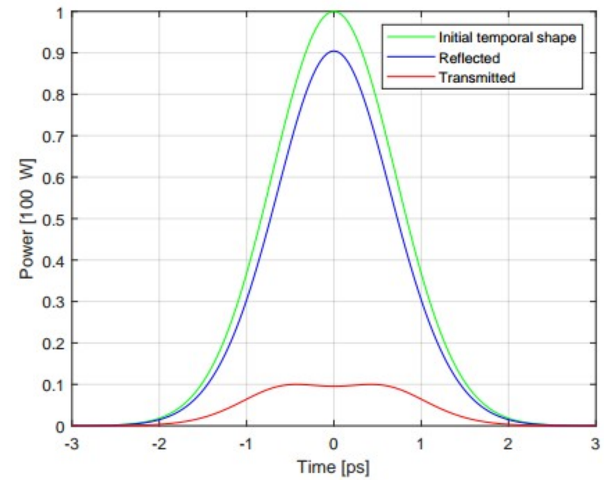
Temporal shapes (green: initial, blue: reflected to cavity, red: output)



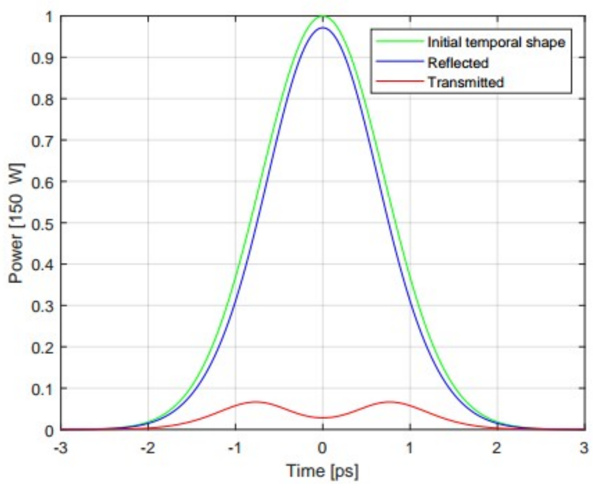
(i) $\times 1$, P_{peak}=1 W



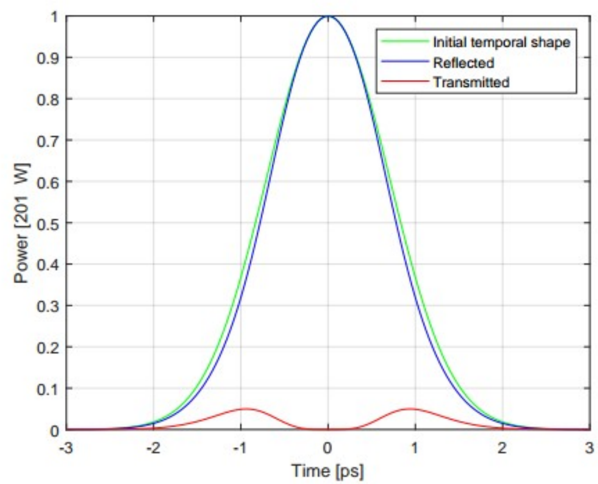
(ii) $\times 2$, P_{peak}=50 W



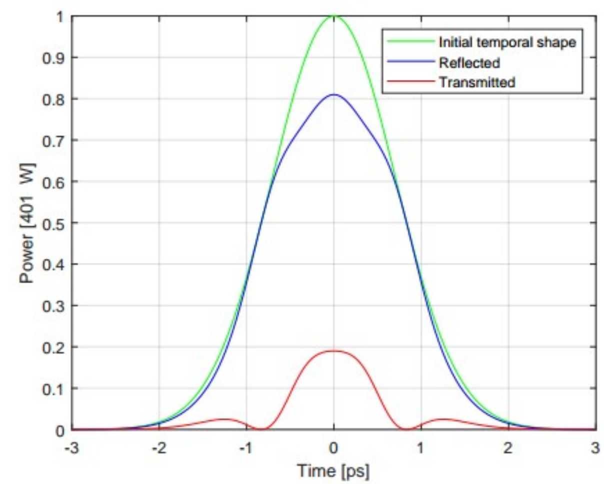
(iii) $\times 3$, P_{peak}=100 W



(iv) $\times 4$, P_{peak}=150 W



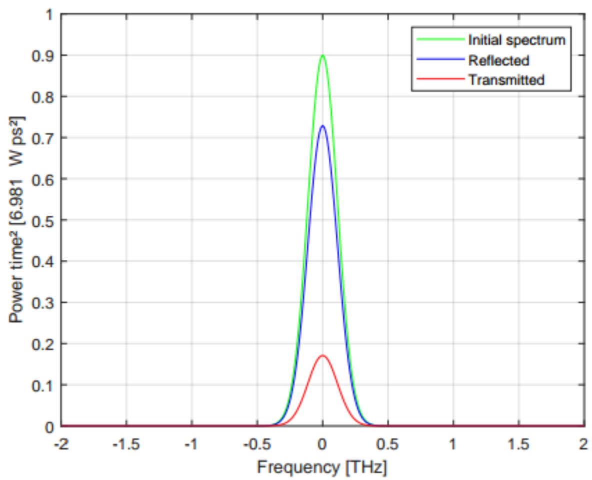
(v) $\times 5$, P_{peak}=201 W



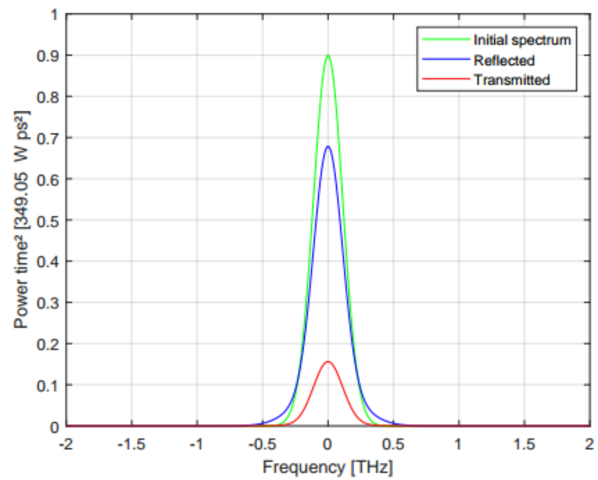
(vi) $\times 6$, P_{peak}=401 W

SPECTRAL DETAIL SHOTS

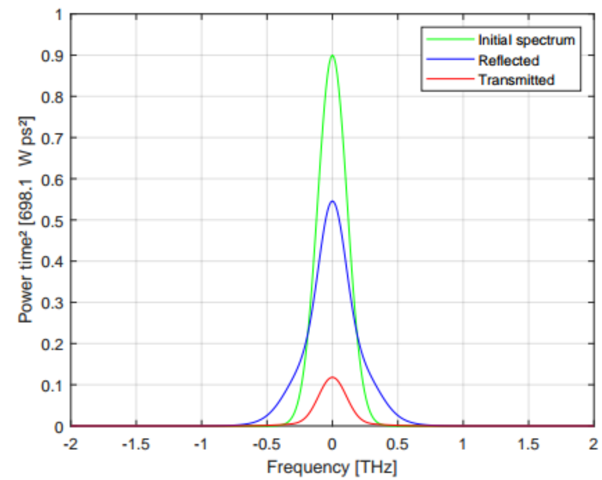
Corresponding spectra (green: initial, blue: reflected to cavity, red: output)



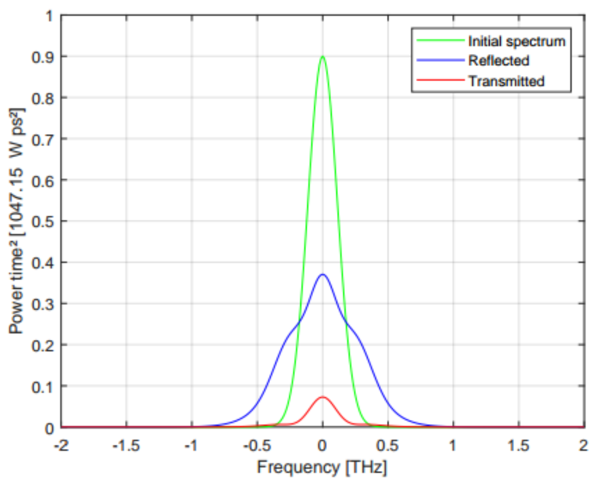
(i) $\times 1$, P_{peak}=1 W.



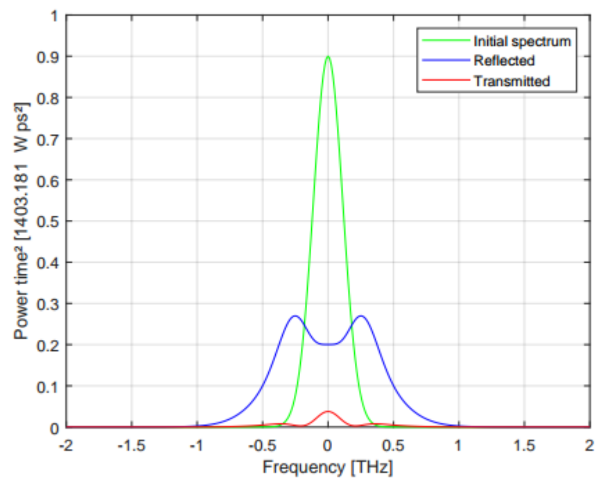
(ii) $\times 2$, P_{peak}=50 W.



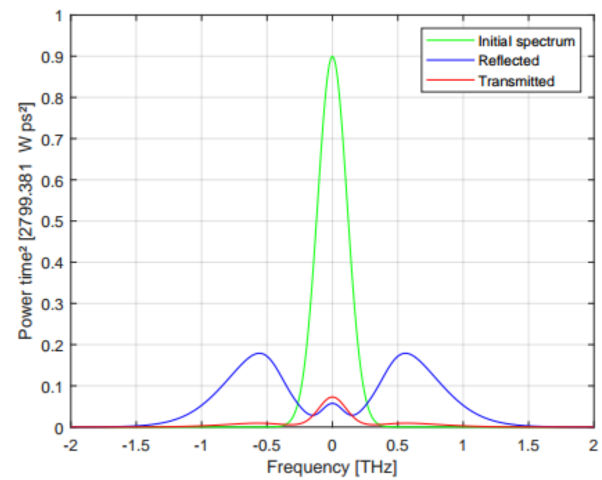
(iii) $\times 3$, P_{peak}=100 W.



(iv) $\times 4$, P_{peak}=150W.

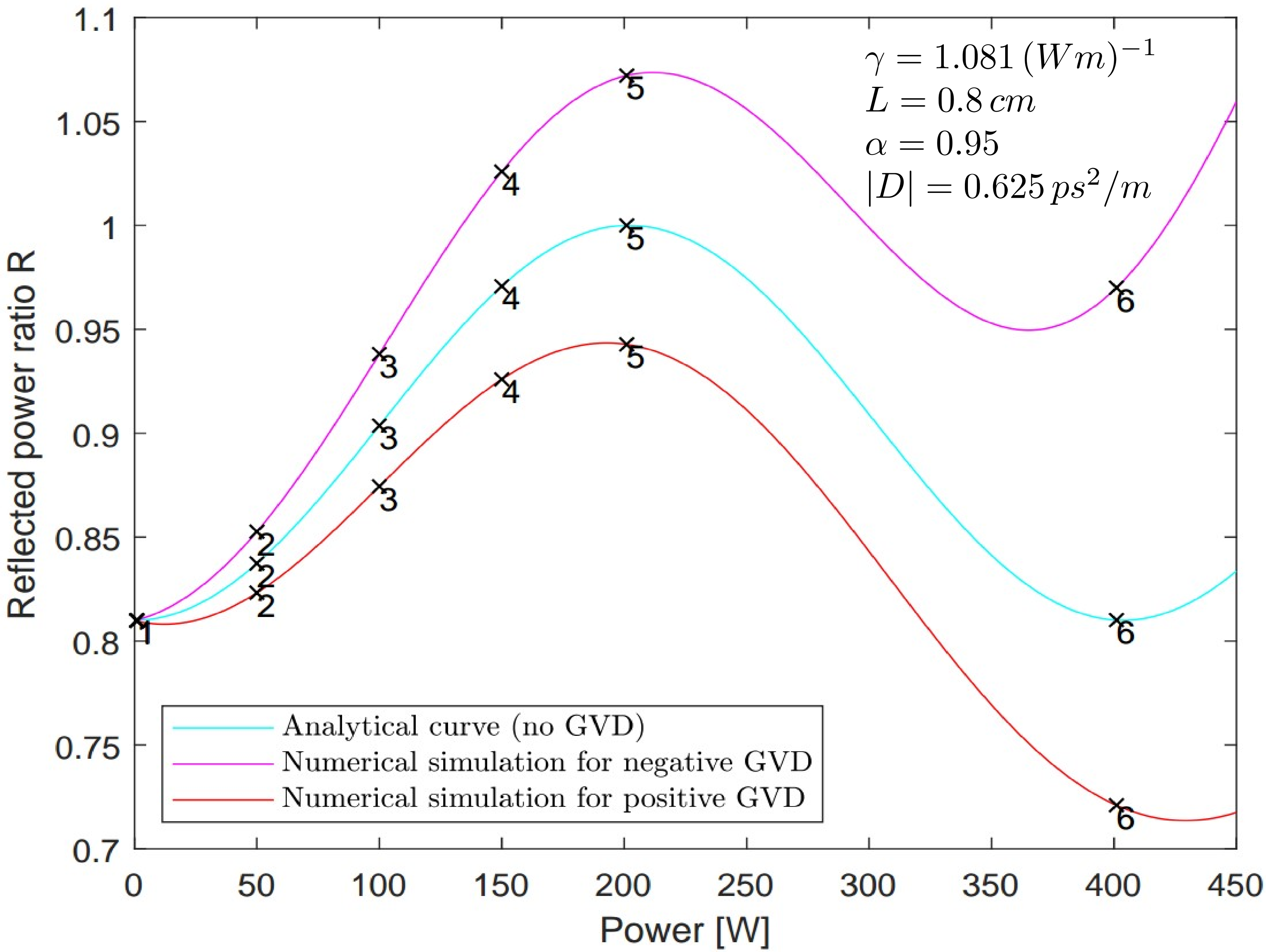


(v) $\times 5$, P_{peak}=201 W.



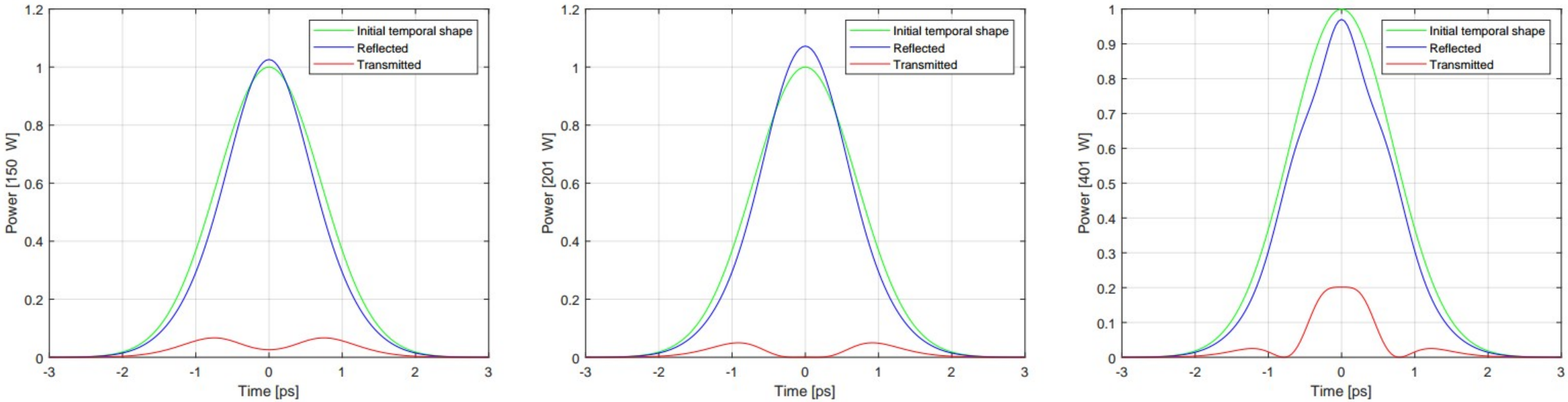
(vi) $\times 6$, P_{peak}=401 W.

REFLECTION CURVES WITH GVD

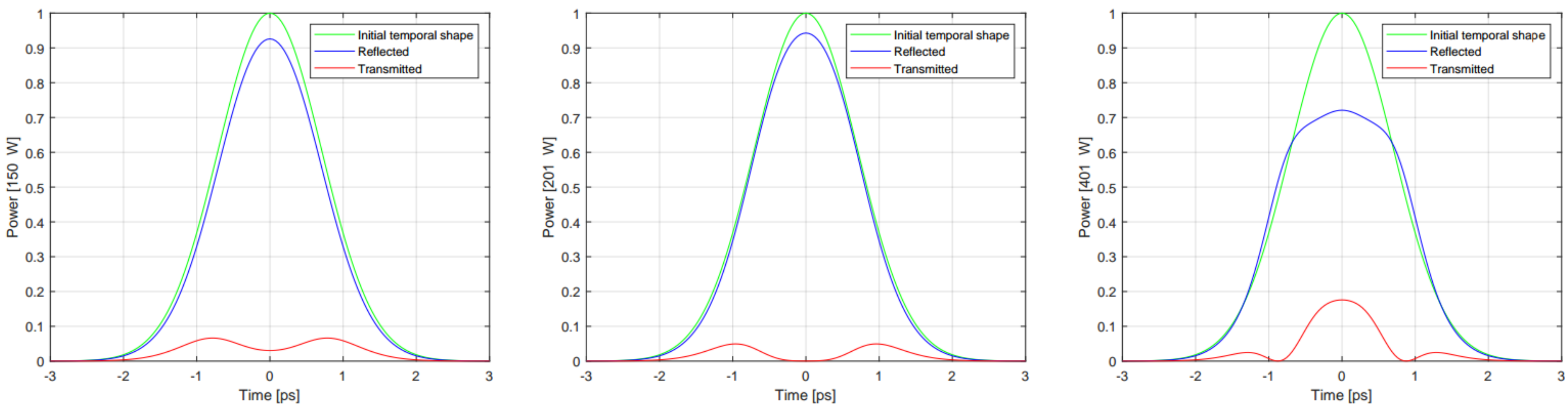


TEMPORAL DETAIL SHOTS WITH GVD

Temporal shapes with negative GVD (D=-0.625 ps²/m) for marker 4, 5 and 6



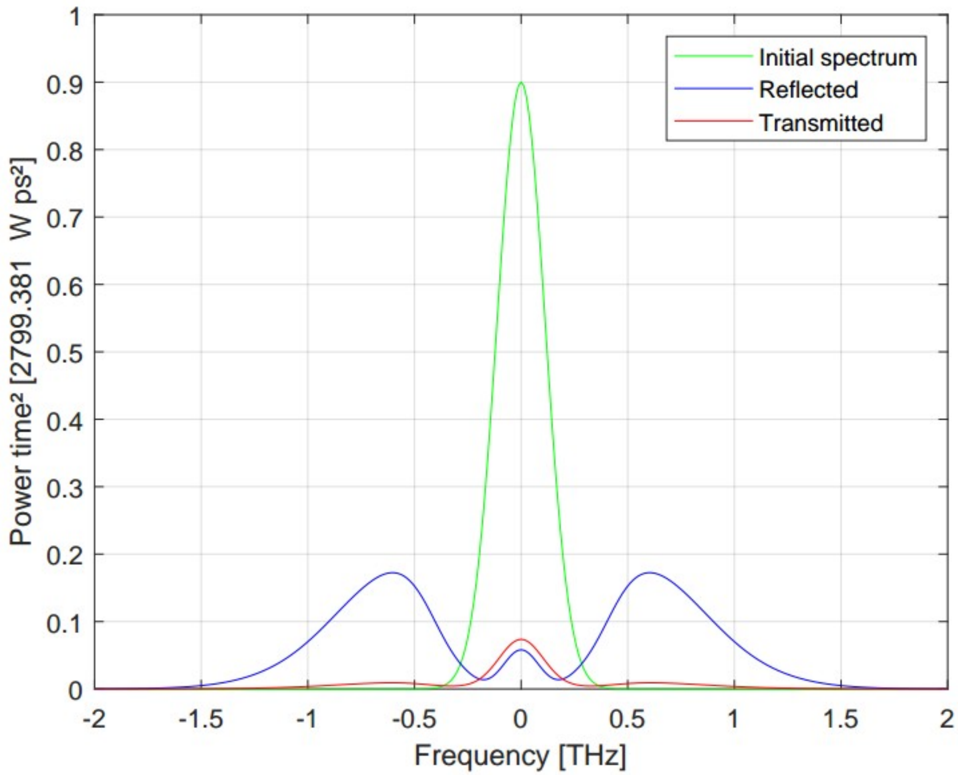
Temporal shapes with positive GVD (D=0.625 ps²/m) for marker 4, 5 and 6



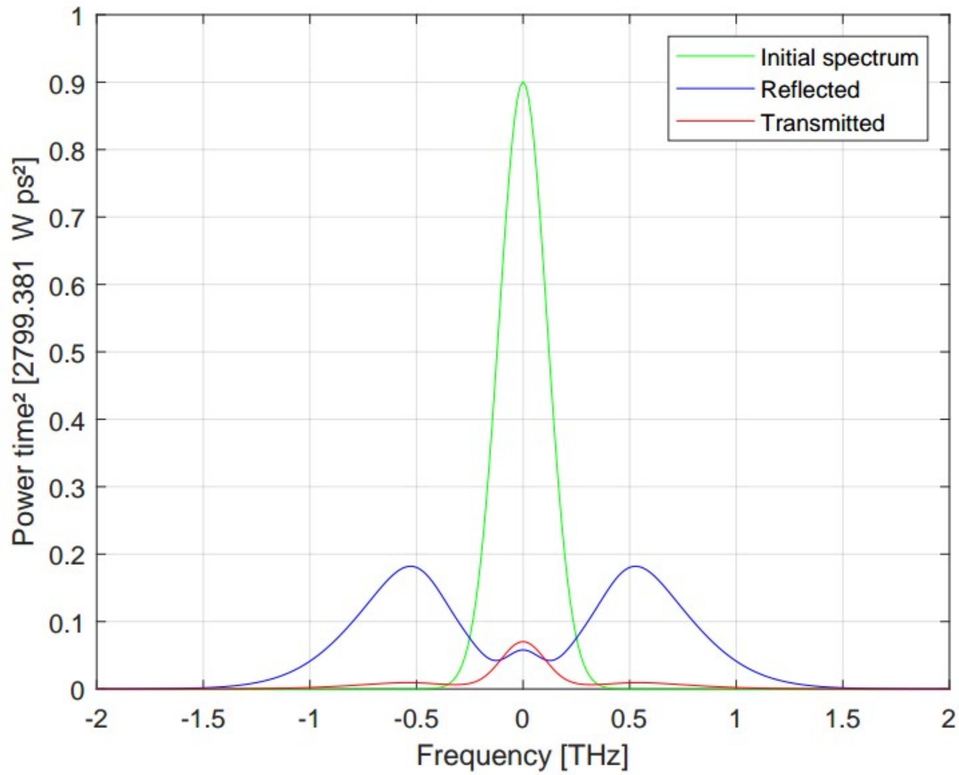
(i) $\times 4,\ P_{peak}$=150 W. (ii) $\times 5,\ P_{peak}$=201 W. (iii) $\times 6,\ P_{peak}$=401 W.

SPECTRAL DETAIL SHOTS WITH GVD

Corresponding spectra for marker 6



(i) $\times 6$ for negative GVD, $D = -0.625\,ps^2/m$.



(ii) $\times 6$ for positive GVD, $D = 0.625\,ps^2/m$.

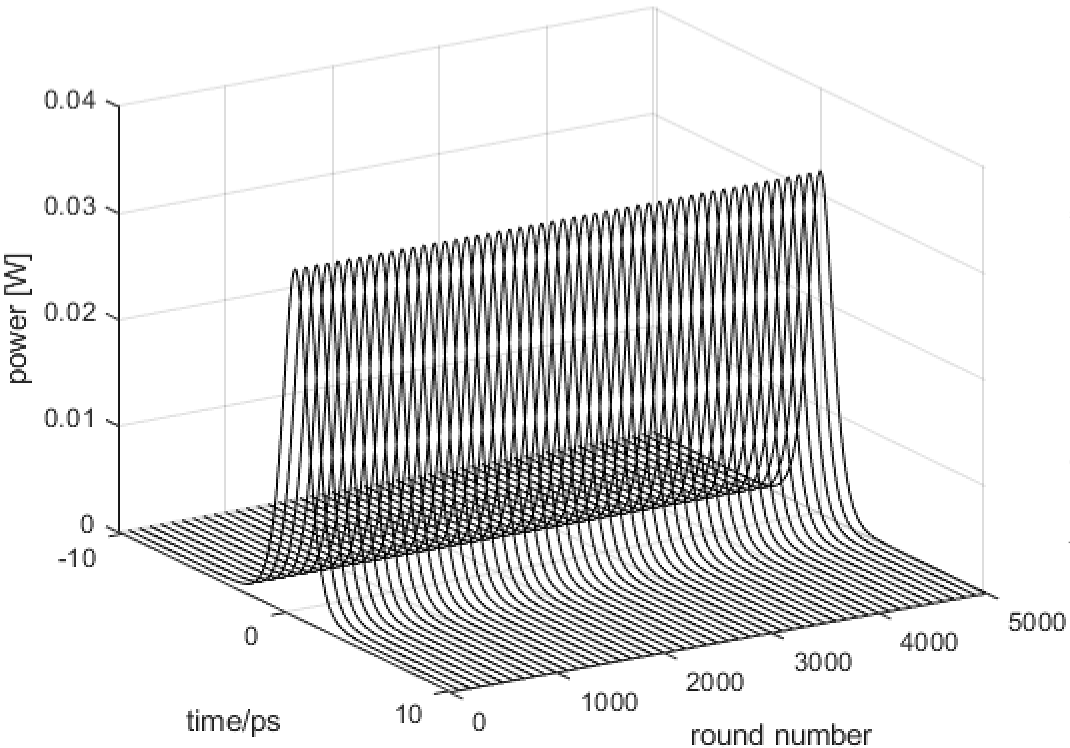
CONCLUSION AND OUTLOOK

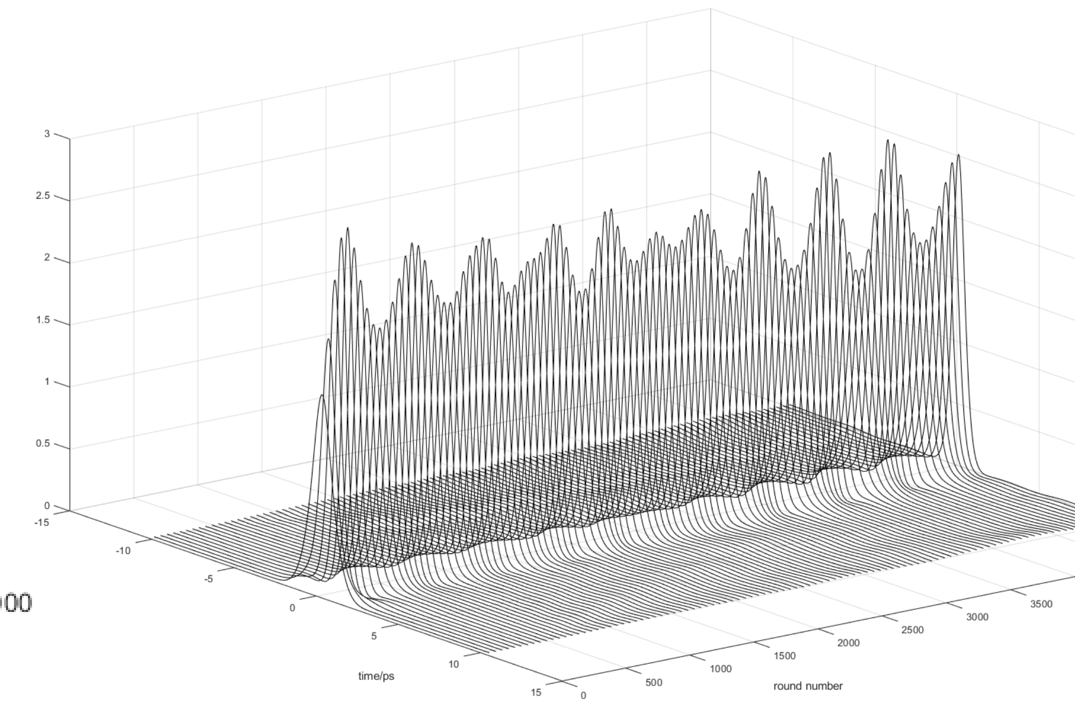
→ The simulation of the NLI works.

→ One must reach high intracavity power to get away from the minimum of R.

→ Test real integrated laser.

→ Find parameter set for full cavity that gives a stable, short, intense pulse.





Stable, but low power

Slightly higher power, but oscillatory.

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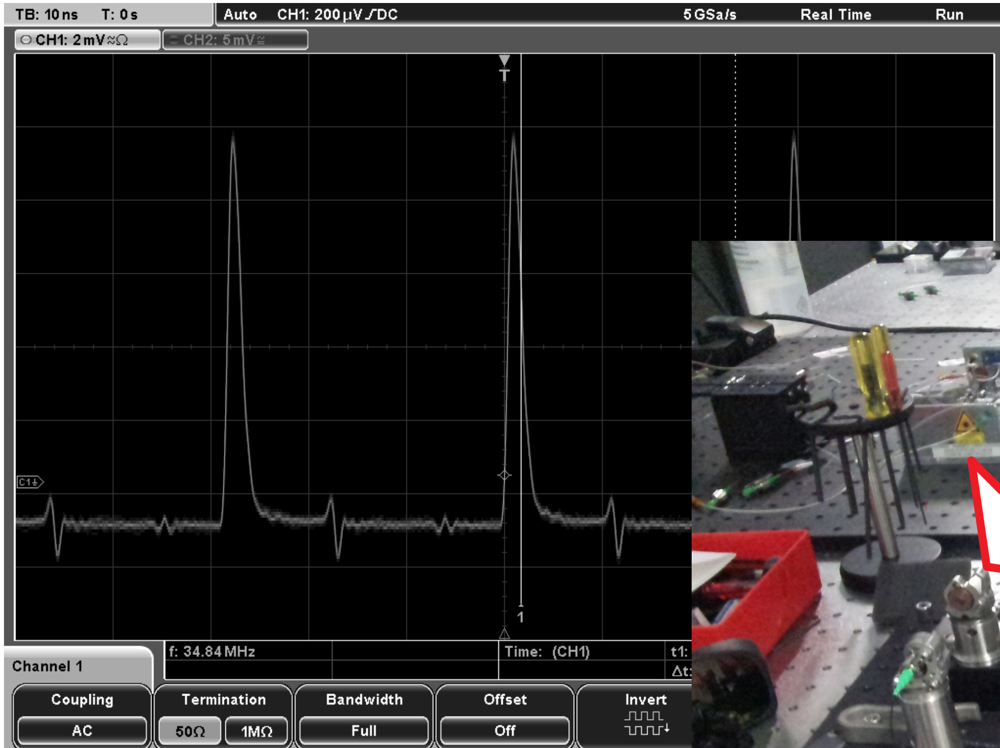
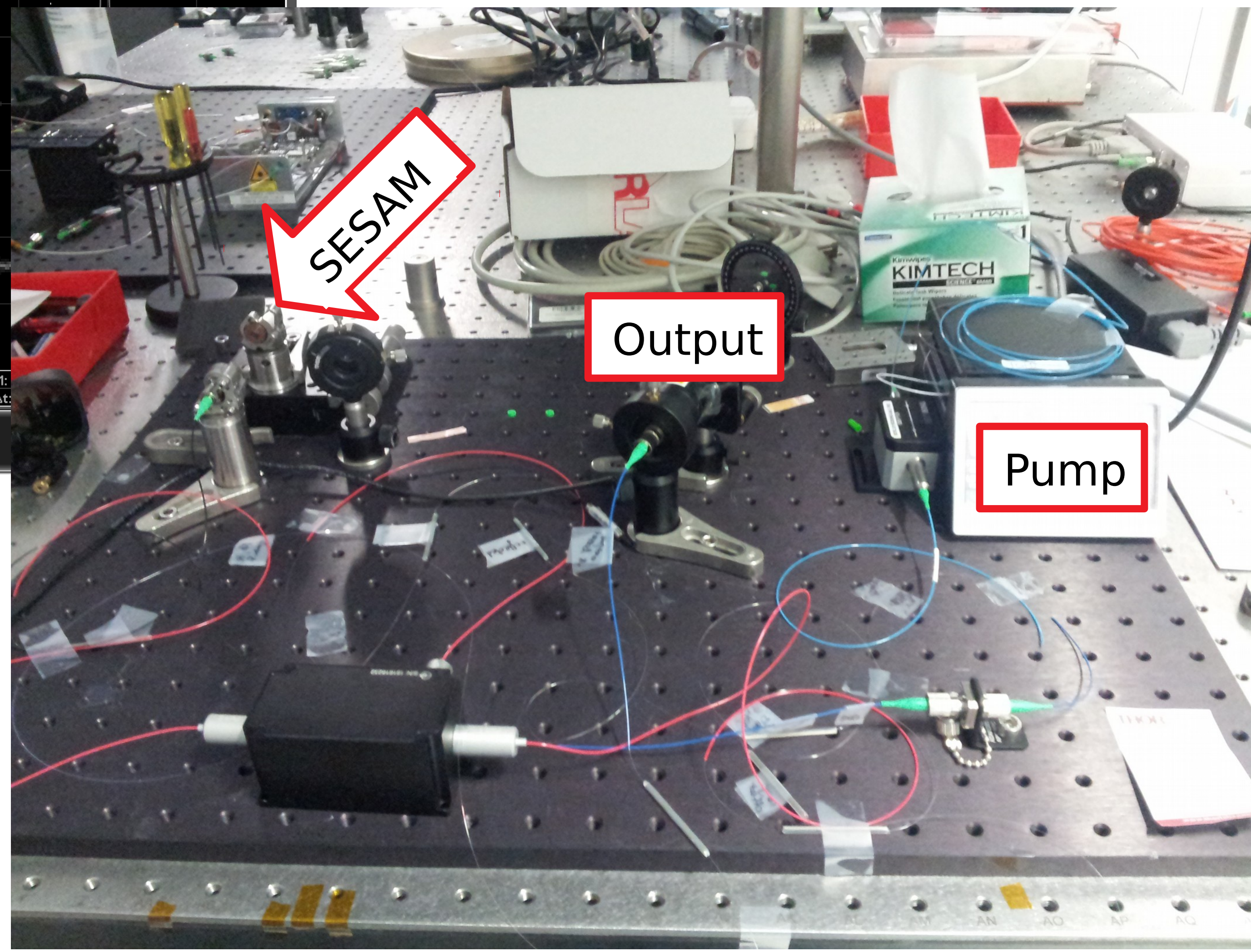
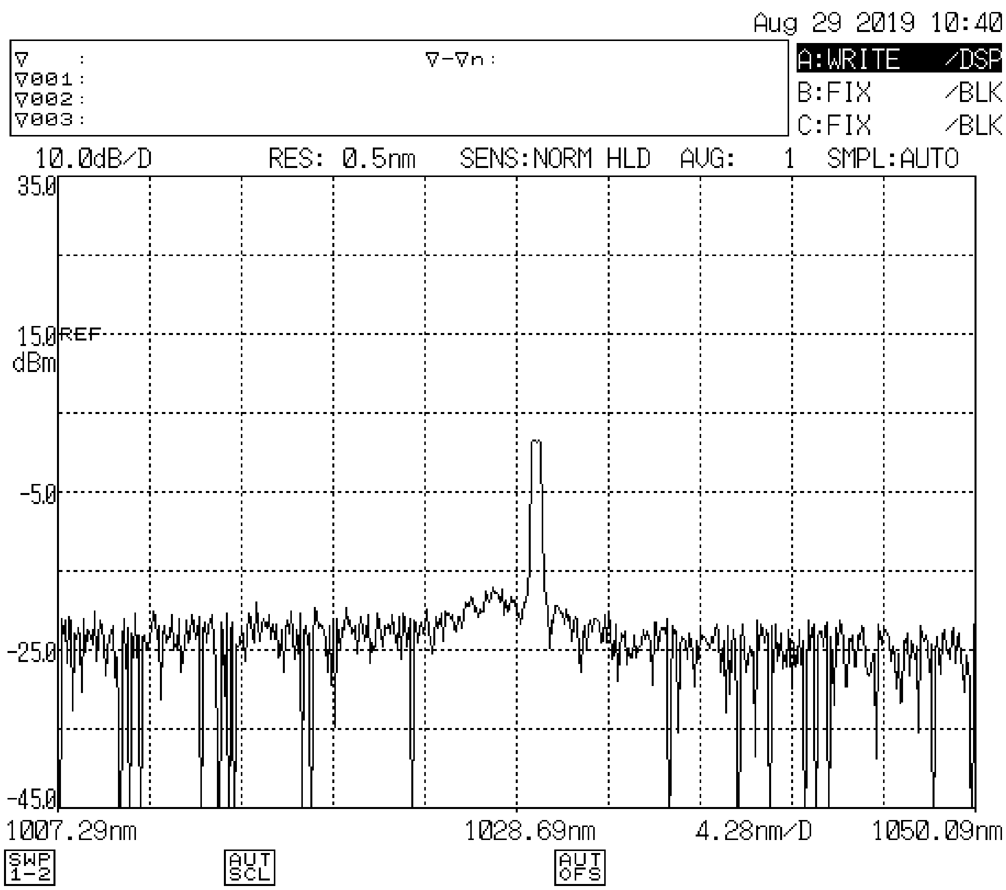
SESAM MODE-LOCKING

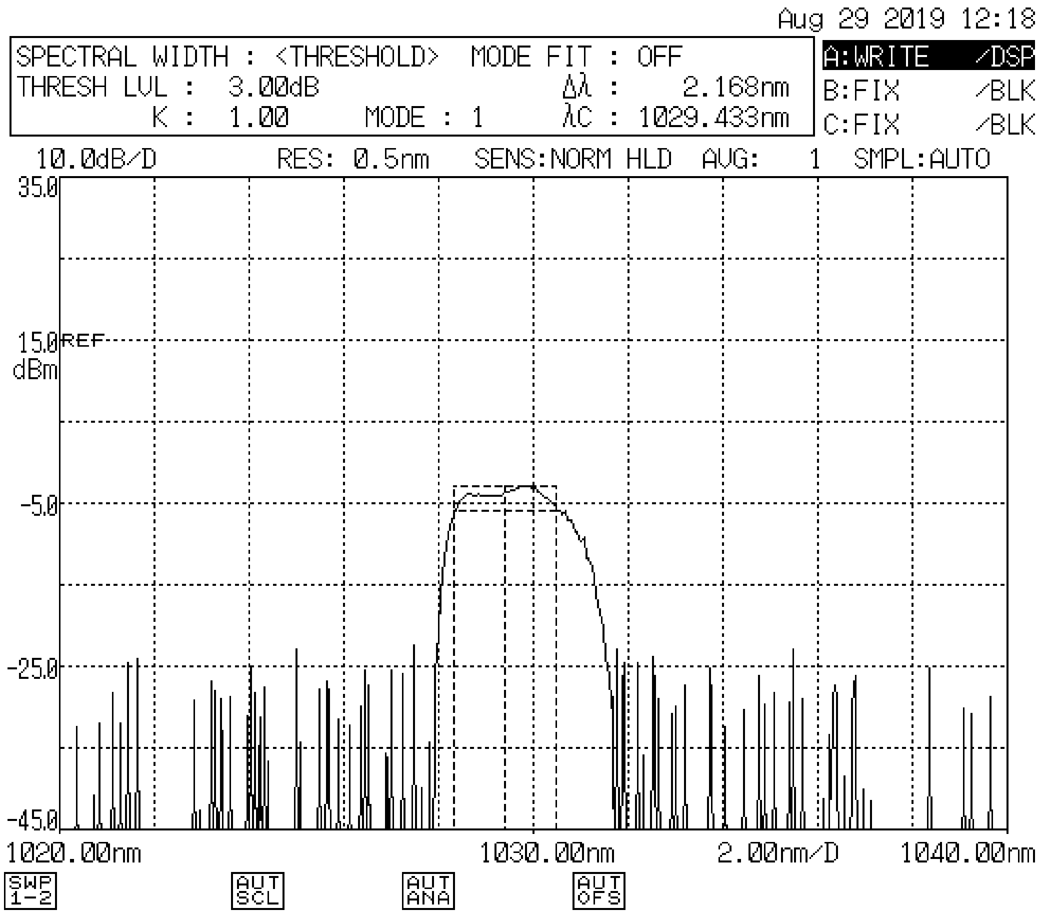




A pulsetrain!

SPECTRA





Spectrum of continuous wave

Spectrum of mode-locked laser

THANK YOU FOR YOUR ATTENTION!