Time-domain simulation of semiconductor laser light with correlated amplitude and phase noise

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Outline

- Motivation
- Physical principle
- Simulation algorithm
- Time-domain results
- Noise spectra
- Applications
- Conclusions

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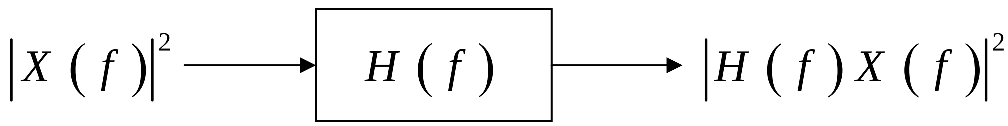
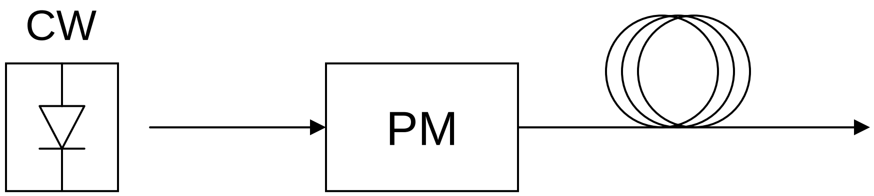
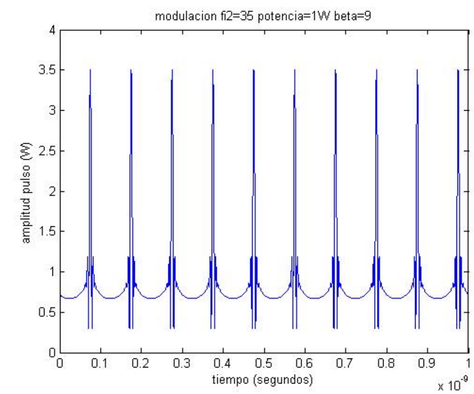
Motivation

Frequency domain analysis is sufficient for LTI systems



Increasing number of applications combine LTI and non-LTI subsystems





Correct system evaluation needs
time-domain noise characterization

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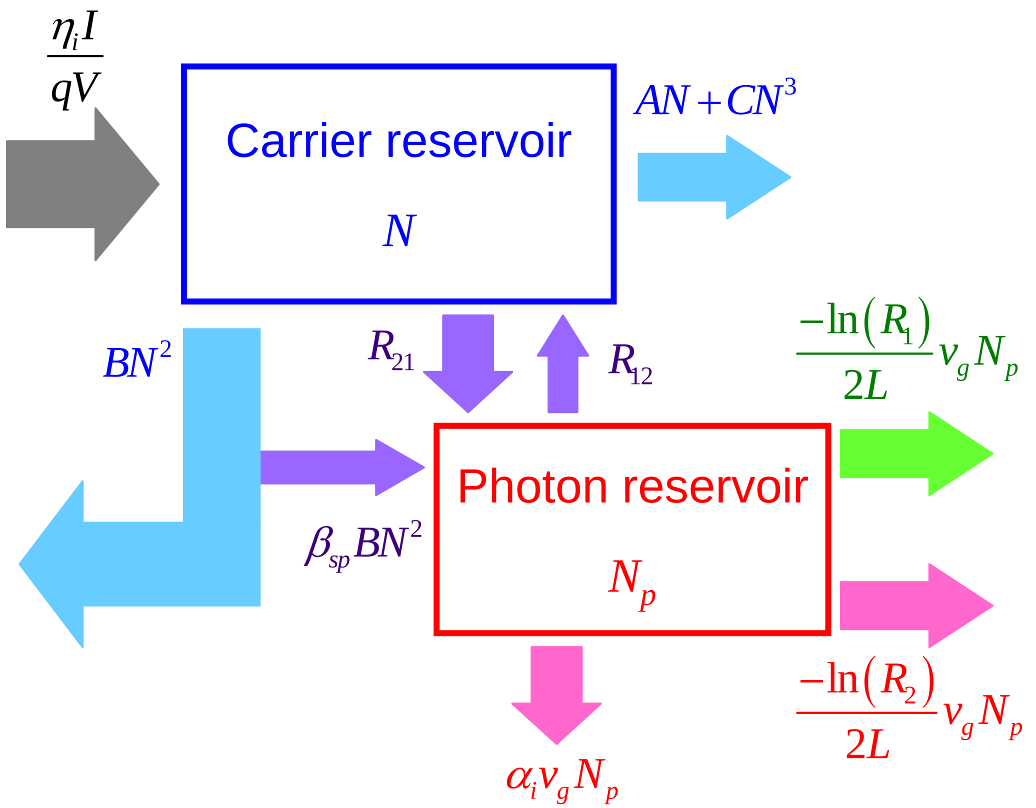
Noise Origin in Semiconductor Lasers



All processes are the sum of individual uncorrelated events

Noise is similar to white noise "colored" by the laser response

The lasing frequency depends on N through reffractive index

Photon output adds partition noise

Spontaneously emitted photons add random phase

Rate Equations and Langevin Picture

$$\frac{dN}{dt} = \frac{\eta_i I}{qV} - AN - CN^3 - BN^2 - R_{21} + R_{12} + F_N$$

Related!!!

Output photon number

$$\frac{dN_p}{dt} = \Gamma R_{21} - \Gamma R_{12} + \Gamma \beta_{sp} BN^2 + \frac{\ln(R_1)}{2L} v_g N_p + \frac{\ln(R_2)}{2L} v_g N_p - \alpha_i v_g N_p + F_P$$

Langevin noise sources F_N and F_P represent randomness in the generation/loss processes (poissonian characteristics)

Effect of noise sources is analogous to substitution of rates with Poisson-distributed variables

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Computation of carrier and photon evolution

Approximation of evolution by numerically solving density rate equations
as difference equations

$$N(t+\Delta t) = N(t) + x_I(t) - x_{nr}(t) - x_{sp}(t) - x_{21}(t) + x_{12}(t)$$

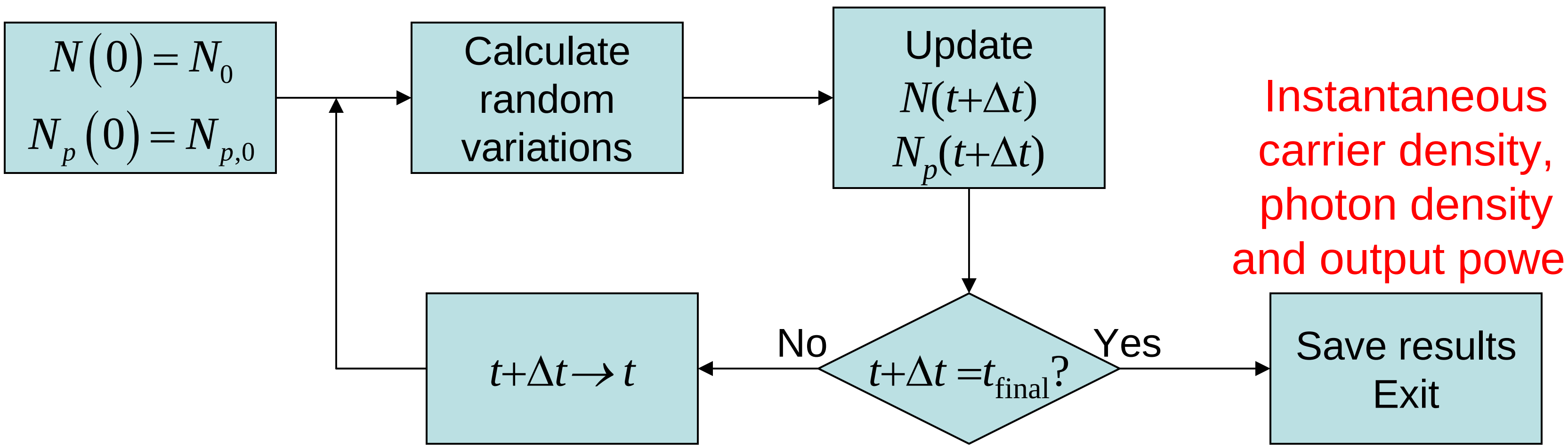
$$N_p(t+\Delta t) = N_p(t) + \Gamma x_{21}(t) - \Gamma x_{12}(t) + \Gamma \beta_{sp} x_{sp}(t) - x_{o1}(t) - x_{o2}(t) - x_l(t)$$

Instantaneous output power may be calculated using $P_{\mathrm{out}}(t) = \dfrac{E_{ph} x_{o1}(t) V_p}{\Delta t}$

Allows the computation of instantaneous carrier and photon densities
Partition noise taken into account

Simulation Algorithm

Self-consistent solution to rate equations provides equilibrium point for given output power $(N_0, N_{p,0})$



Phase noise due to spontaneous emission noise is added as random variable with gaussian probability distribution

$$\Delta f(t) = \frac{\alpha}{4\pi} \Gamma v_g a \left(N(t) - N_0 \right) + x_\phi(t)$$

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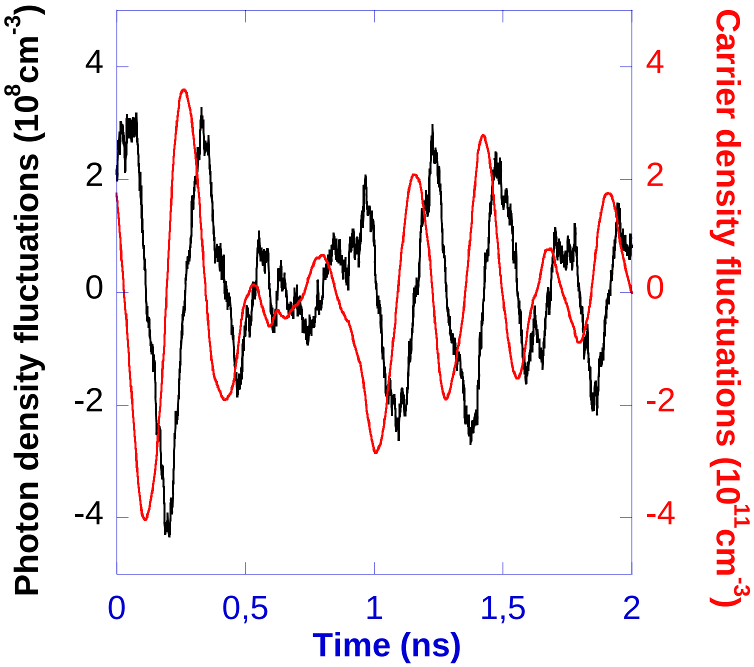
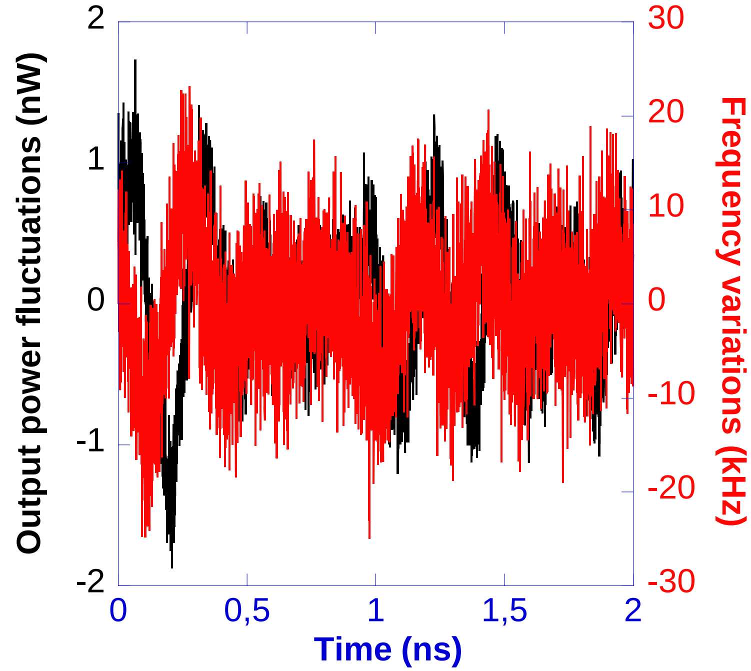
Evolution of Output Power and Frequency

Simulated time evolution of carrier and photon density



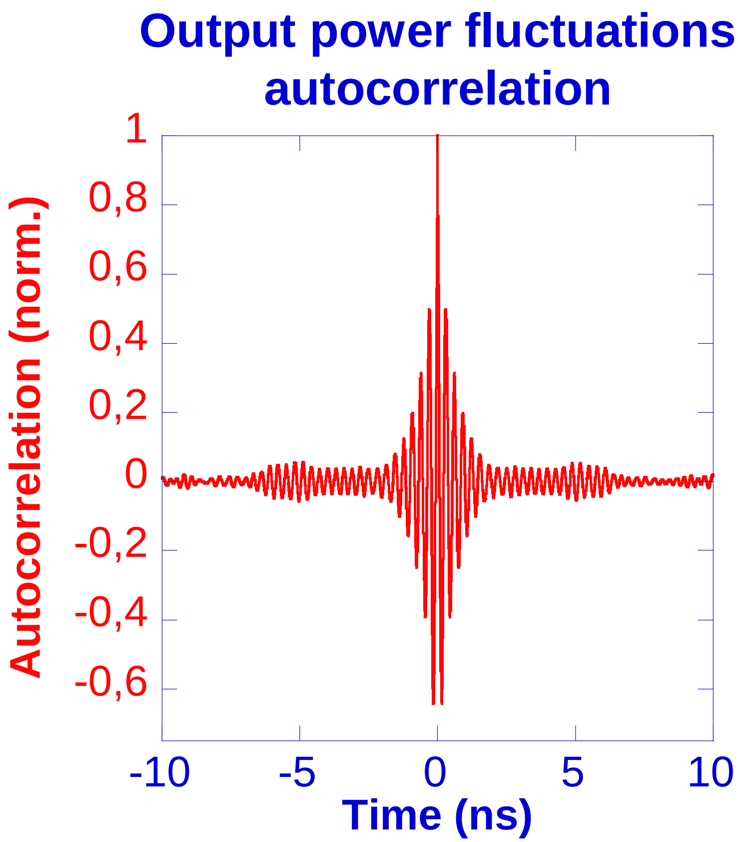
Simulated time evolution of output power and lasing frequency

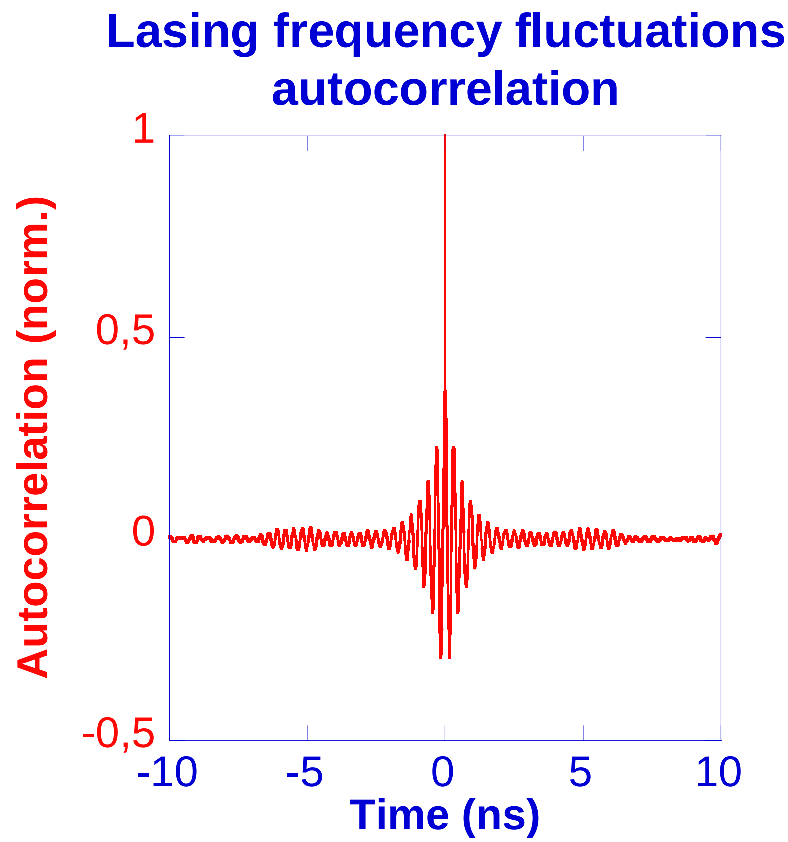


Visible correlation between amplitude and phase noise

Optical power variations trail frequency variations by about $\pi/2$

Autocorrelations





Partition noise makes the output power fluctuations autocorrelation “noisier”

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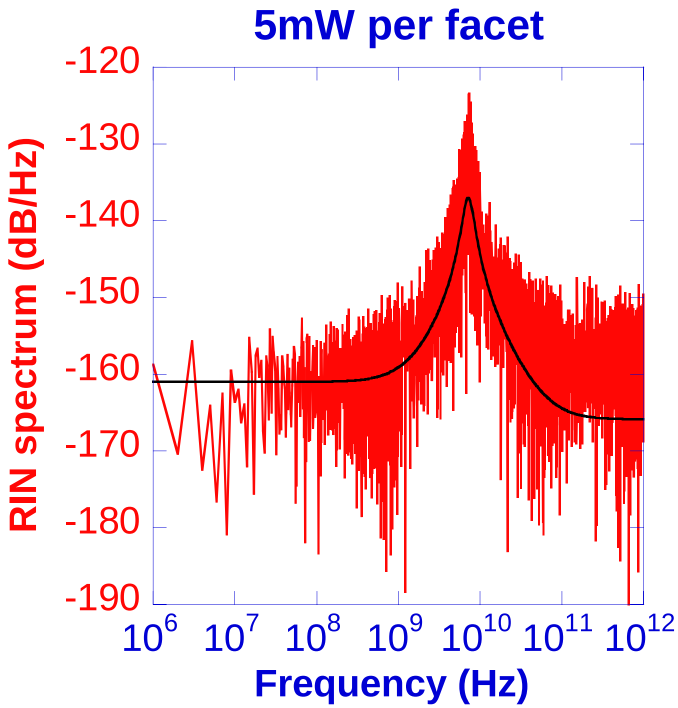
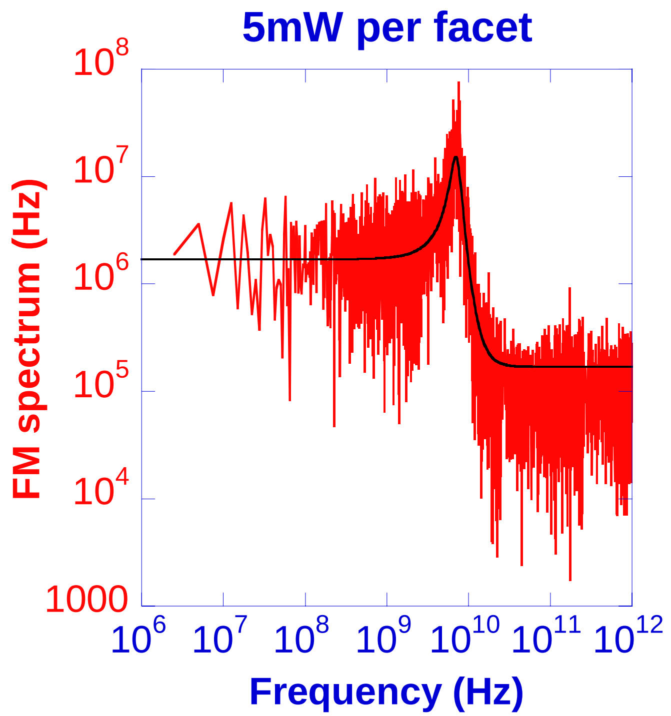
RIN Spectra



Good agreement between computed results and previously exising theoretical results

Frequency Noise Spectra



Good agreement between computed results and previously exising theoretical results

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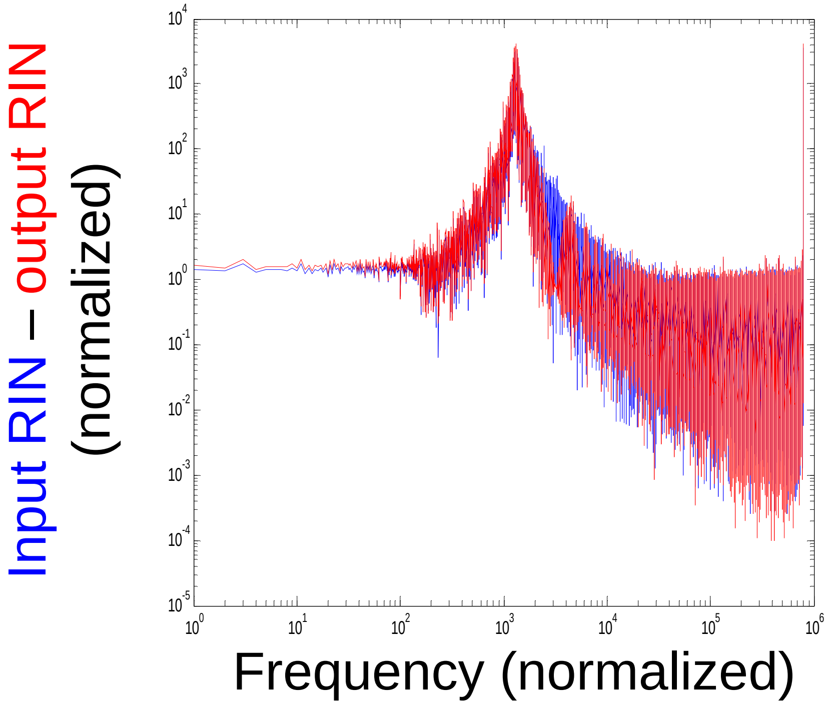
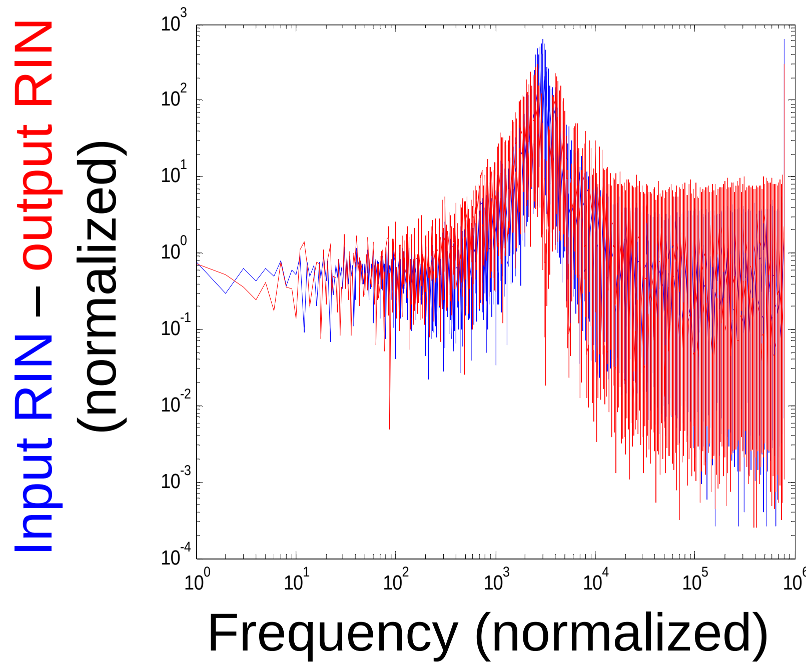
RIN Reduction

1mW per facet

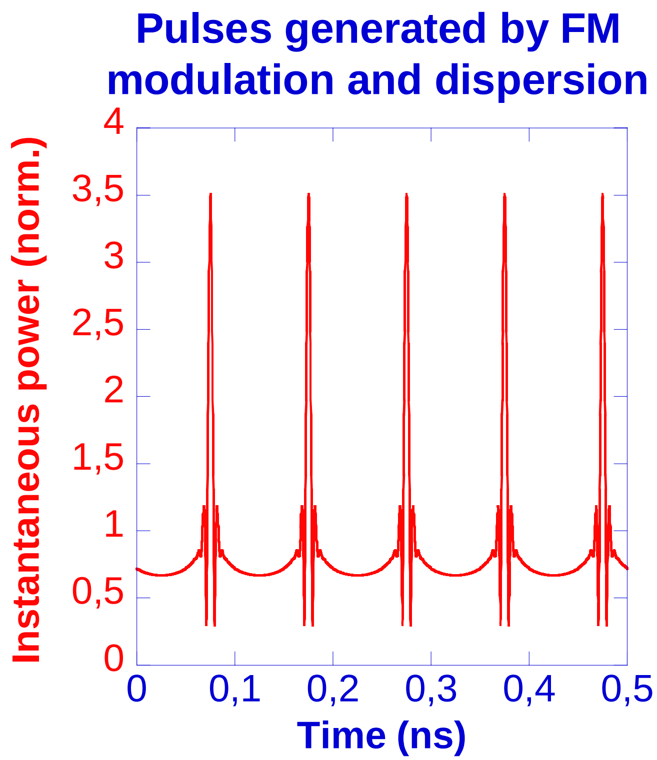


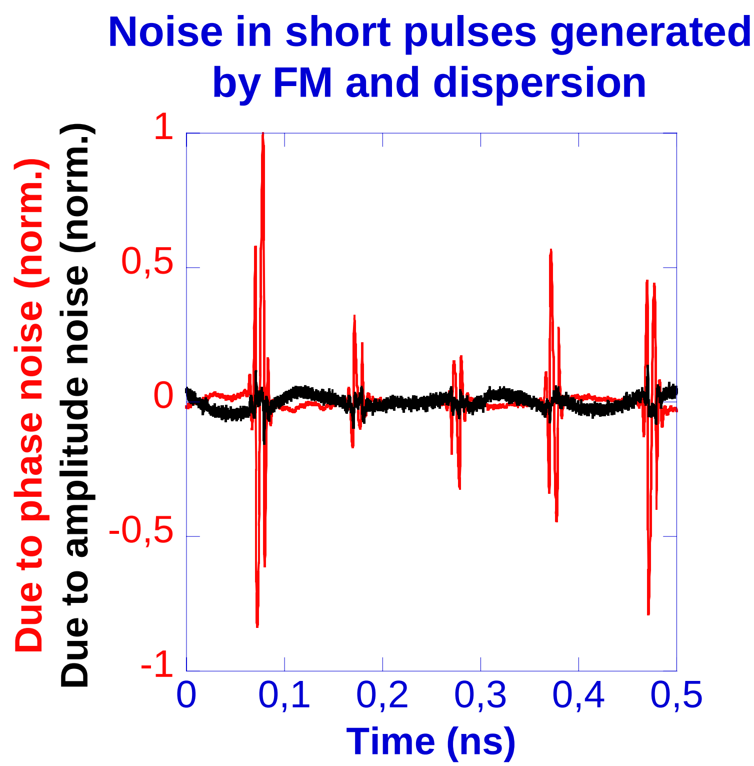
5mW per facet



Future work: check with existing theory (Vahala & Newkirk)

Noise in Short Pulses





Future work: Evaluate critical parameters and reduce noise

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Conclusions

- **Time-domain algorithm** that computes laser noise based on **physical principle** of operation
- **Correlation** ensured by use of coupled **density-rate equations**
- "Natural" introduction of **partition noise** – artificial introduction of **spontaneous emission** effect on phase noise
- Results **match predictions** from existing frequency-domain models
- Possible application to systems combining both **LTI and non-LTI** components