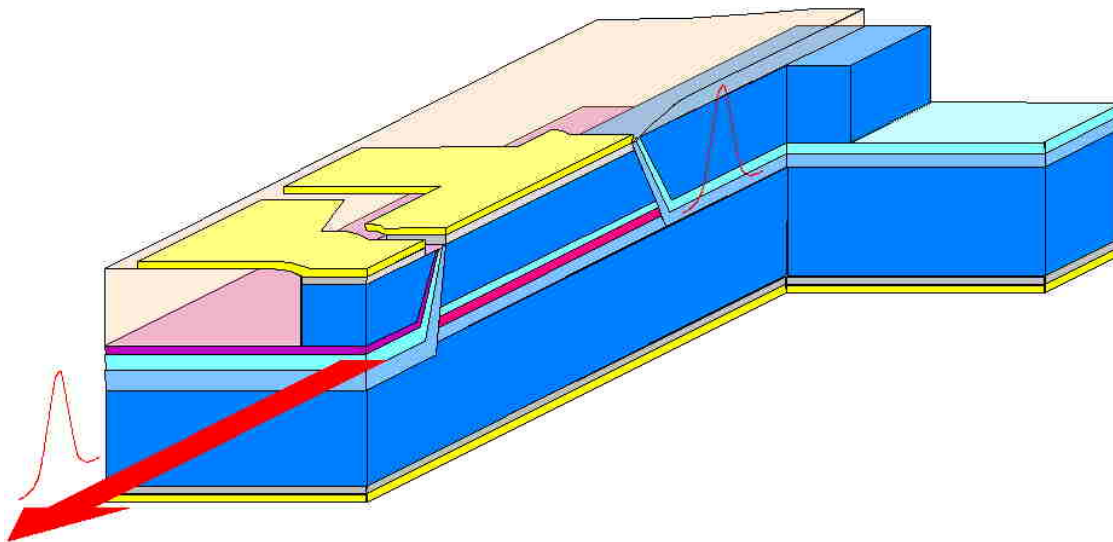


Design and Measurement of an Ultrafast Absorber for Monolithically Integrated InGaAsP/InP Mode-Locked Laser Diodes



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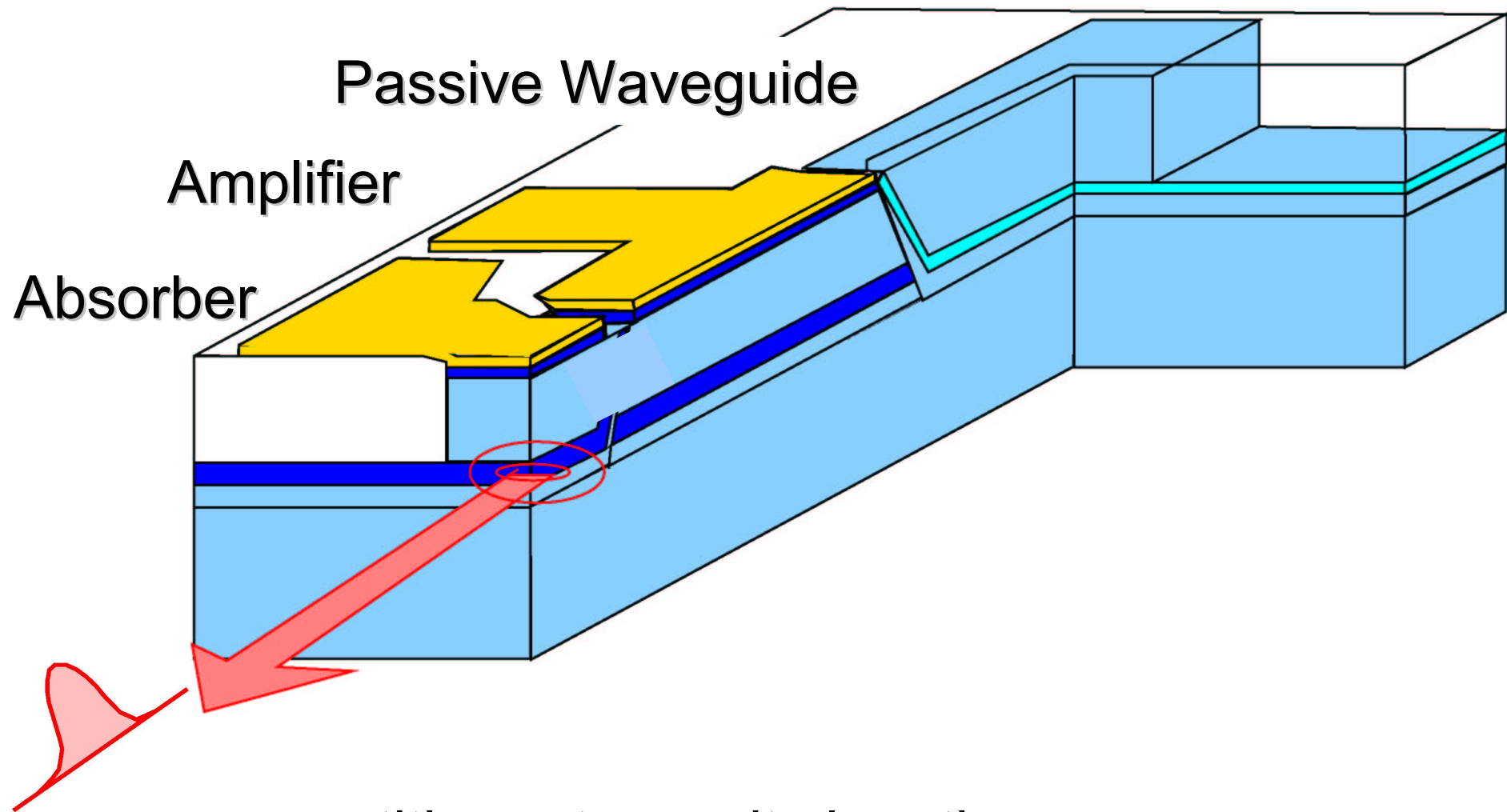
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Outline

- Tbit/s OTDM Fiber Networks require $< 1\text{ps}$
Pulse Sources
- 3 Sections Mode-Locked Laser Diode (MLLD)
 - numerical dynamic model
 - pulse formation process
 - motivation for a fast absorber
- Uni Travelling Carrier (UTC)-Absorber
key design requirements:
 - fast absorption recovery
 - low saturation energypump-probe measurements
- Conclusions and Outlook

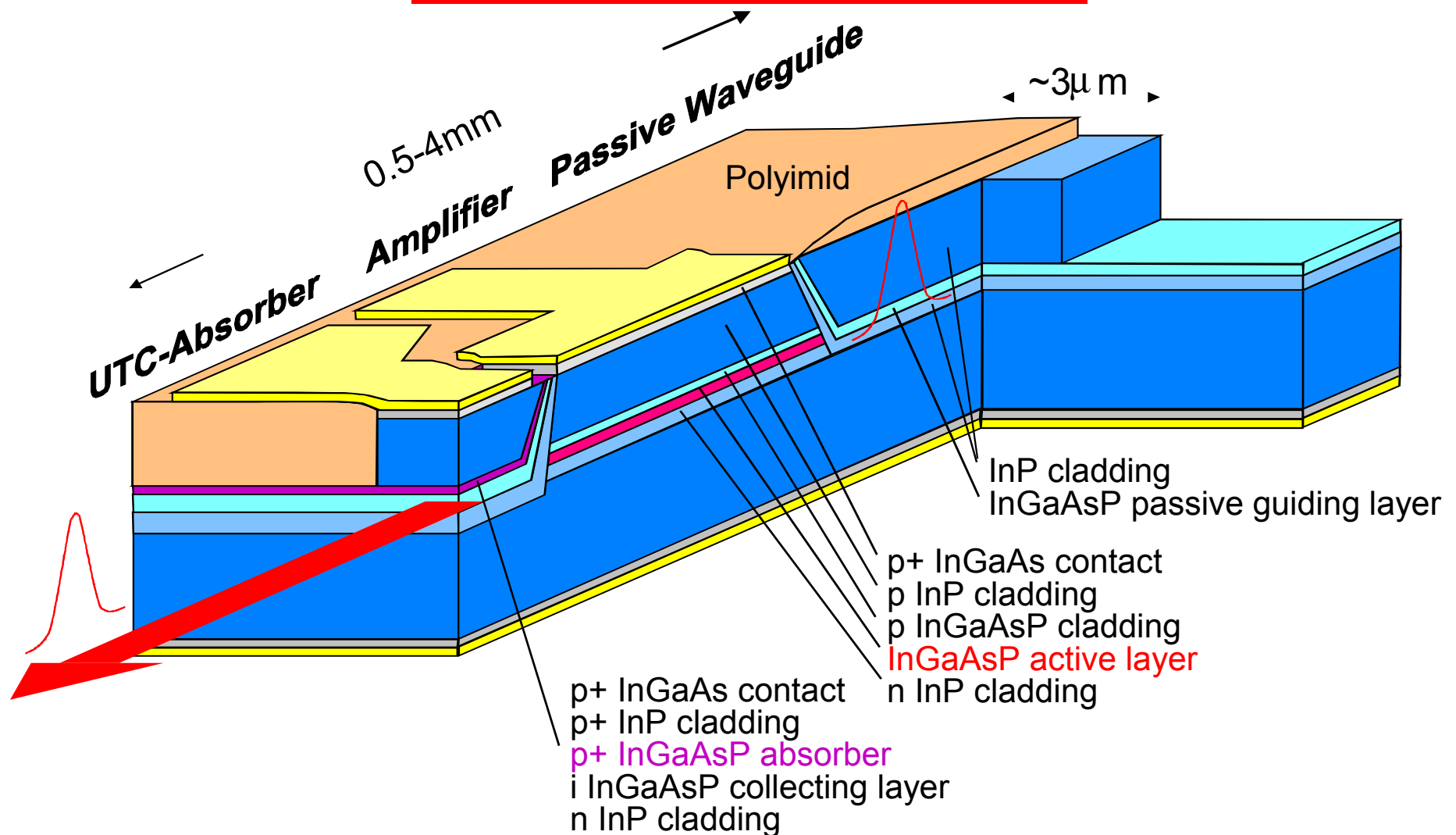
MLLD Operating Principle



Pulse repetition rate: cavity length

Pulses formation: interplay of gain and loss dynamics

3-Sections MLLD



Different structures for absorber and amplifier to optimize independently gain and loss dynamics

3-Sections MLLD

Generic Numerical Model:

Carrier rate equation:

$$\frac{\partial N}{\partial t} = \frac{\mu I}{qV_{act}} - R(N) - g_m \frac{\Gamma P}{\hbar \omega_0 \sigma}$$

Non-linear dynamics:

(saturation energy, carrier heating, spectral hole burning)

$$\frac{\partial g_{N,T}}{\partial t} = - \frac{g_0 - g_{N,T}}{\tau_R} - g_m \frac{P}{E_{sat,N,T}}$$

Recovery time constants τ_R
Saturation energies E_{sat}

Propagation equation:

$$\frac{\partial}{\partial z} A(z, \tau) = \left[\frac{j}{2} \beta_2 \frac{\partial^2}{\partial \tau^2} - \frac{\Gamma \gamma}{2\sigma} (1 + j\alpha_{tpa}) |A(z, \tau)|^2 \right] A(z, \tau)$$

Passive media

$$+ \frac{j}{2} [\Gamma g_m(\tau, \omega) (1 + j\alpha) - \alpha_{int}] A(z, \tau)$$

Active material: gain and phase

$$- \left[j \frac{1}{2} \frac{\partial g_m(\tau, \omega)}{\partial \omega} \bigg|_{\omega_0} \frac{\partial}{\partial t} + \frac{1}{4} \frac{\partial^2 g_m(\tau, \omega)}{\partial \omega^2} \bigg|_{\omega_0} \frac{\partial^2}{\partial \tau^2} \right] A(z, \tau)$$

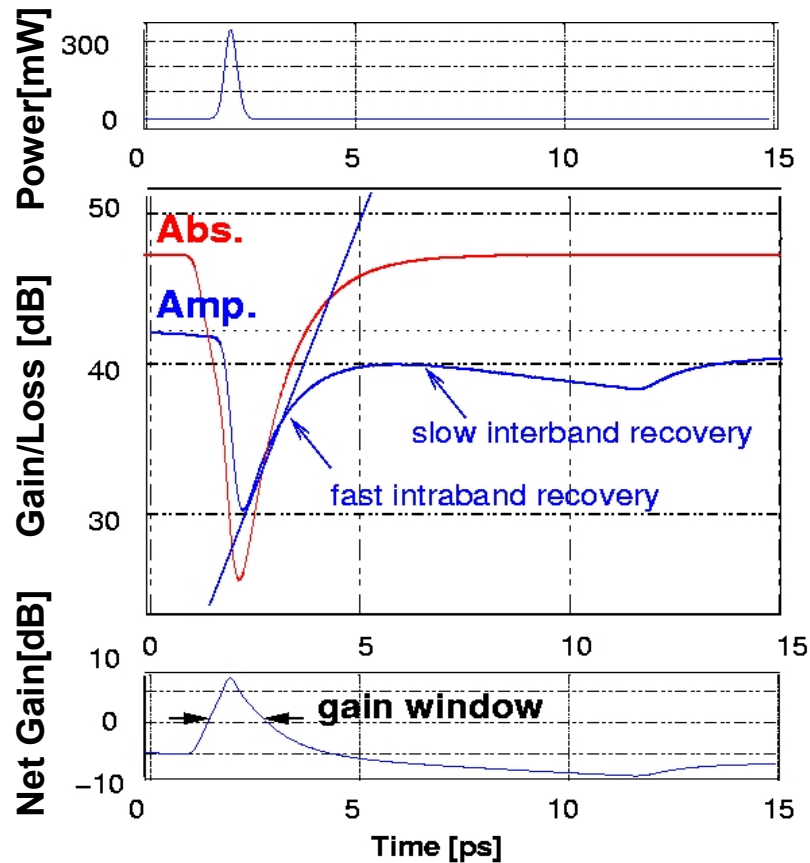
Gain dispersion (parabolic gain approximation)

TPA coefficient γ
Group velocity dispersion β_2

Parameters must be determined experimentally

Pulse Formation:

Operation Principle:



Net gain window:

absorption saturation



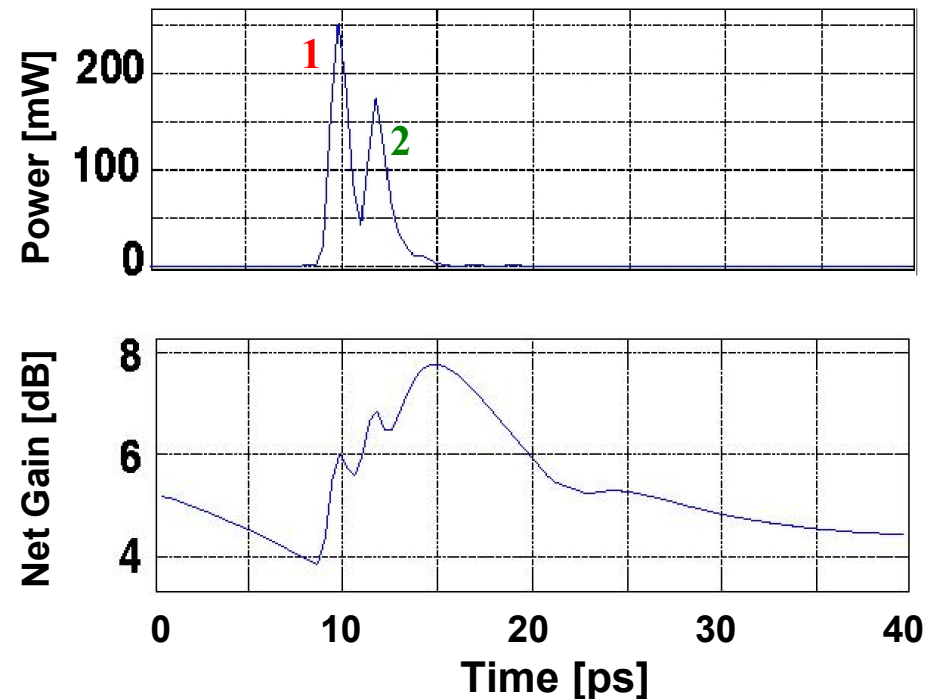
absorption recovery and gain saturation

Problem:

- ultrafast (ps) gain partial recovery
- slow reversed-biased SOA absorber



unstable, multiple pulses of 1 - 3ps



Pulse Formation:

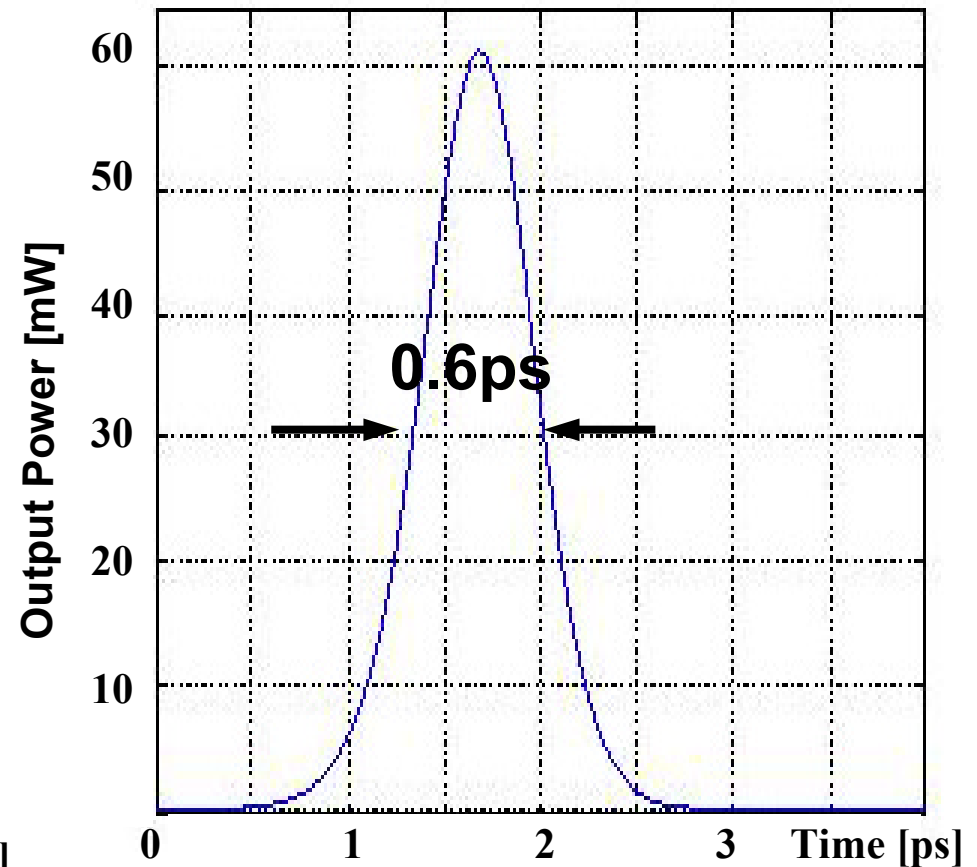
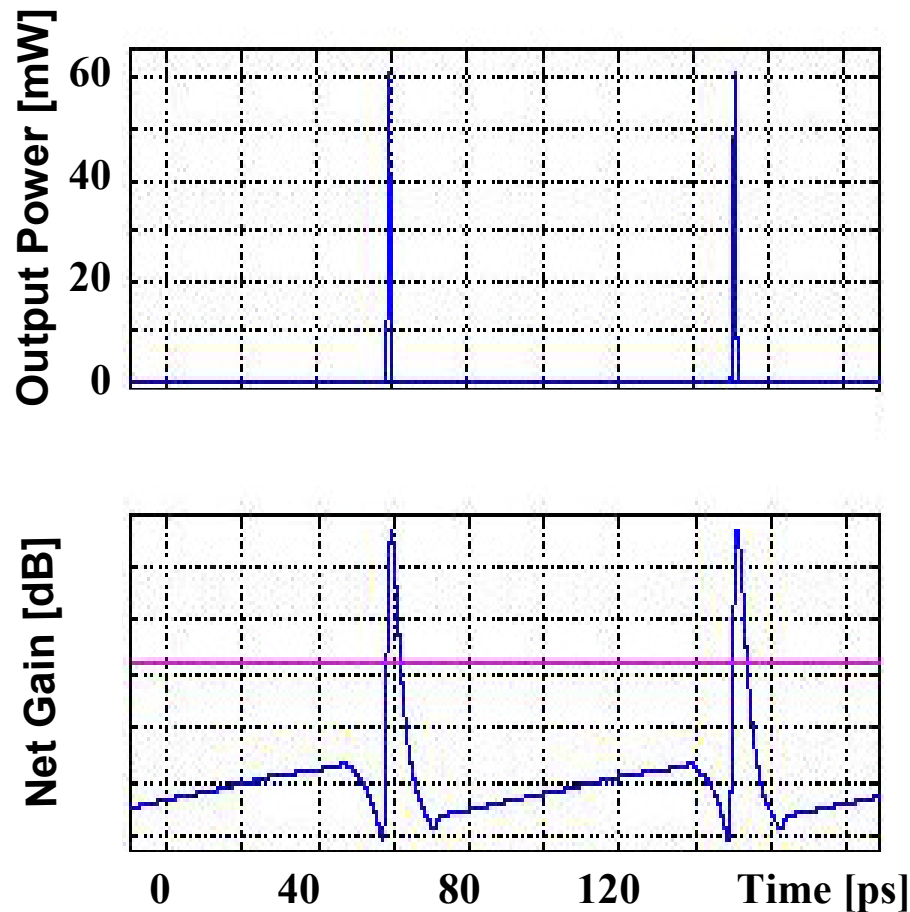
Pulse Stability vs. Absorber Recovery Time:

Absorber Recovery Time

Absorber Length		20ps	10ps	7.5ps	5ps	2.5ps	1ps
	90μm	No Pulse					
	80μm						
	70μm	Q-Switching				0.8ps (100mW)	0.6ps (80mW)
	60μm				0.9ps (140mW)	0.8ps (120mW)	0.6ps (80mW)
	50μm				0.9ps (140mW)	0.8ps (300mW)	
	40μm					0.8ps (300mW)	
	30μm	Unstable Multiple Pulses					
	20μm						
	10μm						

Pulse Formation:

Optimized Pulses from MLLD with Fast Absorber:



Solution: Integration of a fast ($\tau < 2\text{ps}$) absorber

UTC – Absorber Design

Requirements:

- Fast recovery time $\rightarrow \tau < 2\text{ps}$
- Low saturation energy $\rightarrow E_{\text{sat}} < 1\text{pJ}$
- Good Interfaces $\rightarrow r_t < 10^{-4}$

Design:

- Uni traveling carrier - absorber
- Mode centering on absorbing layer
- Mode matching between sections

UTC*-Concept:

Electron and holes generation in thin p-doped absorbing layer

Holes: majority carriers (fast response governed by the dielectric time constant)

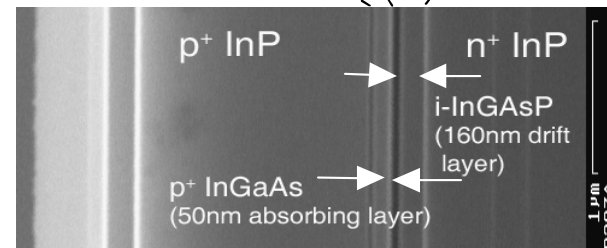
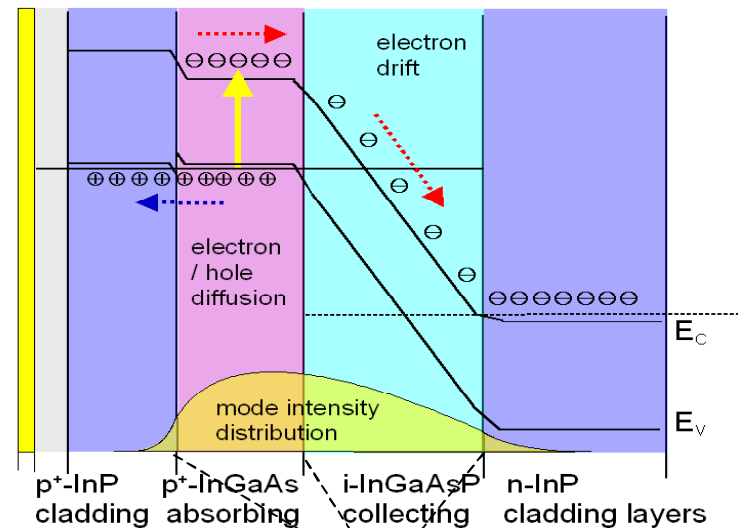
$$\tau_{\text{relax}} \sim 100\text{fs} @ p > 4 \cdot 10^{17} \text{cm}^{-3}$$

Only high mobility electrons drift through the collecting layer

$$\tau_{\text{diff},e} = \frac{w_a^2}{3D_n} + \frac{w_a}{v_{\text{therm}}} \sim 0.25\text{ps}$$

$$\tau_{\text{drift},e} = \frac{w_c}{v_{\text{sat}}} \sim 0.25 - 1\text{ps}$$

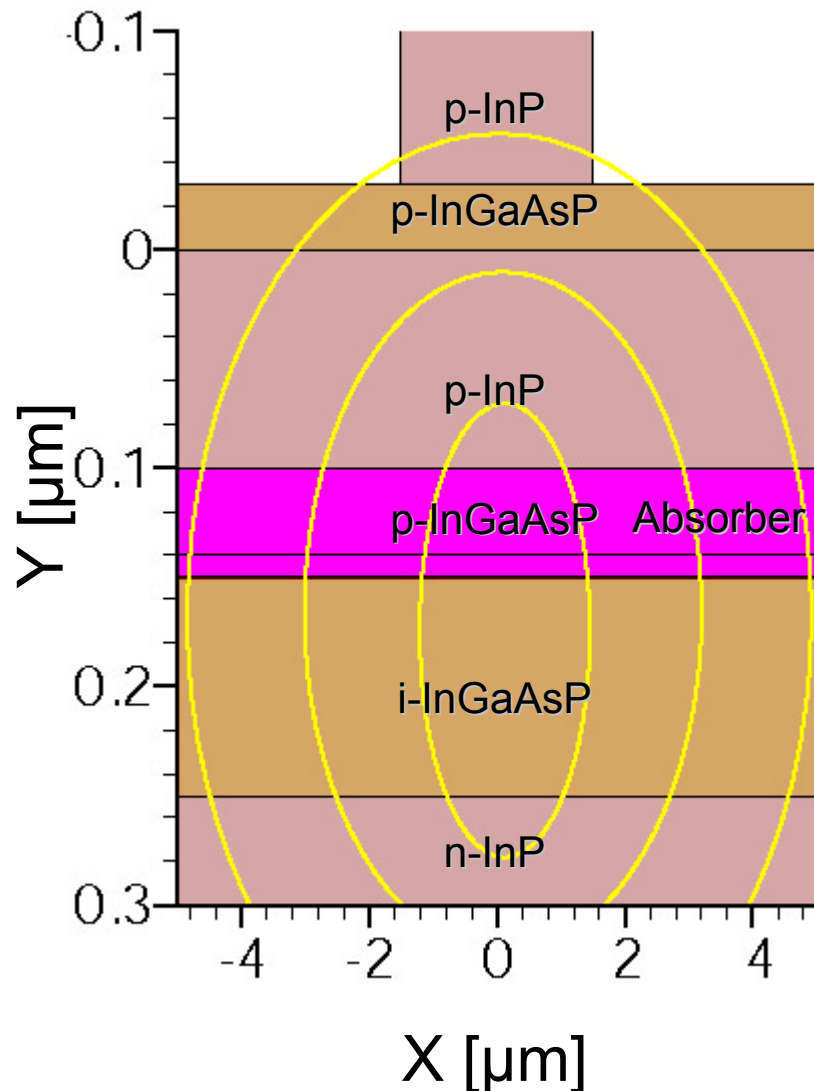
UTC Schematic and SEM:



UTC – Absorber Design

2D-Simulations

(DESSIS [®]ISE)



Impulse response:

100fs square light pulse

Light generates electrons and holes in the absorbing InGaAsP region

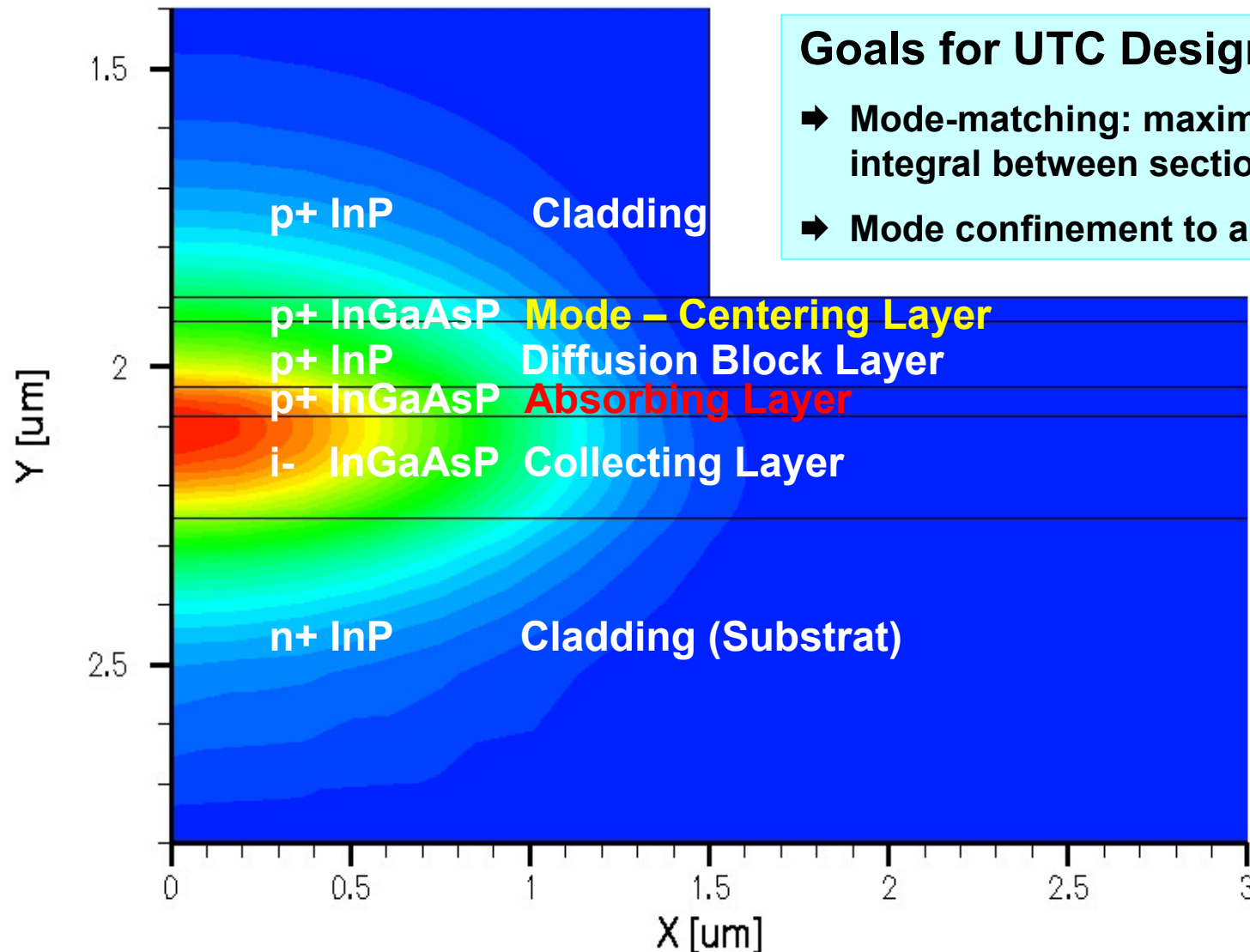
Drift-diffusion model used for carrier extraction



Absorption recovery $\alpha(t) \sim n(t)$

UTC – Absorber Design

Mode Intensity:



Goals for UTC Design:

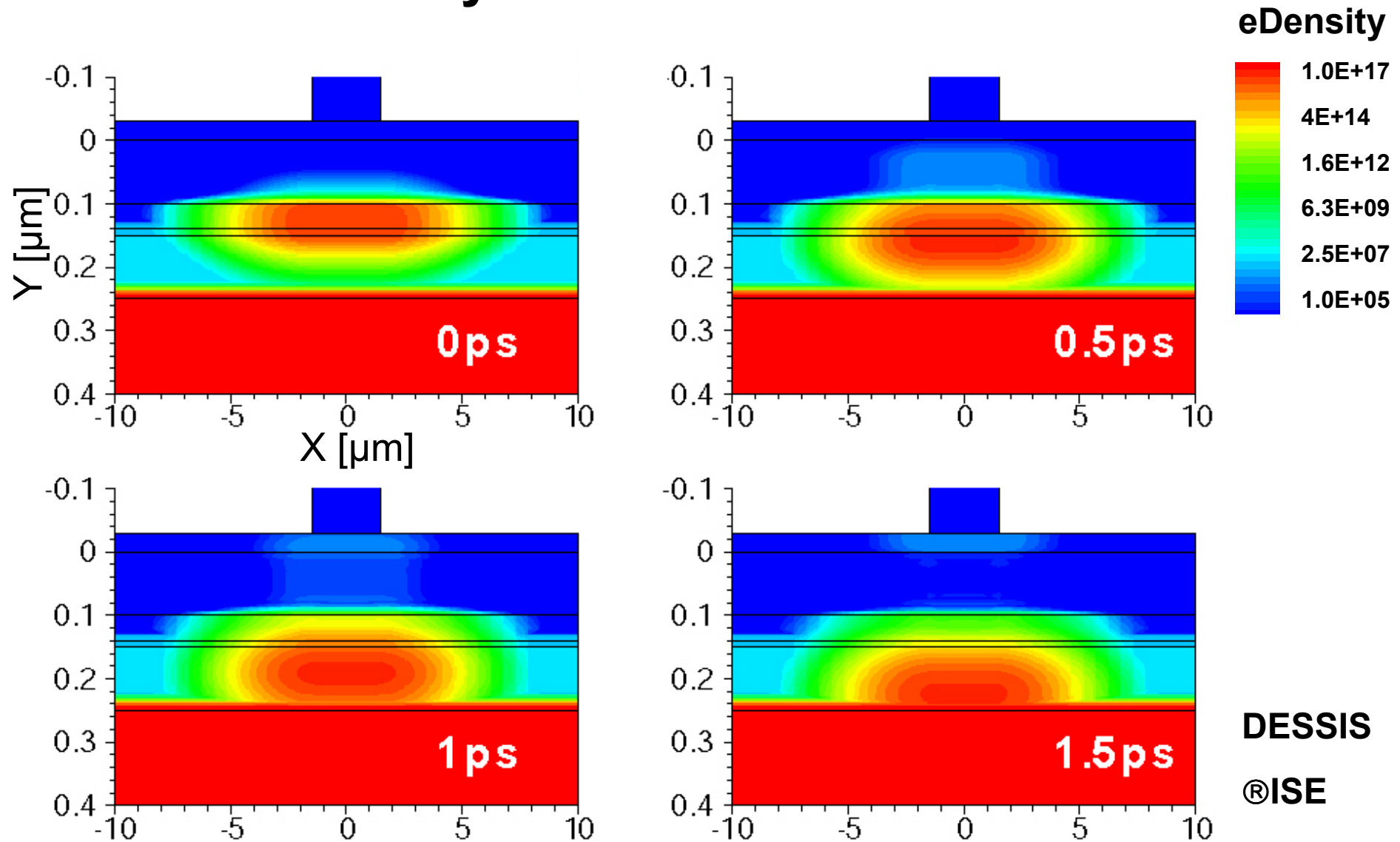
- ➔ Mode-matching: maximized overlap integral between sections
- ➔ Mode confinement to absorbing layer

DESSIS

®ISE

UTC – Absorber Design

Electron Density Transient:



UTC – Absorber Design

Simulation of Saturation Energy:

$$\frac{\partial \alpha_{N,abs}}{\partial t} = \frac{\alpha_0 - \alpha_{N,abs}}{\tau_{abs}} - \alpha_m \frac{P}{E_{sat,N,abs}}$$

$$E_{Sat,N,abs} = \frac{\hbar \omega}{\lambda} \frac{\sigma}{a_n \Gamma}$$

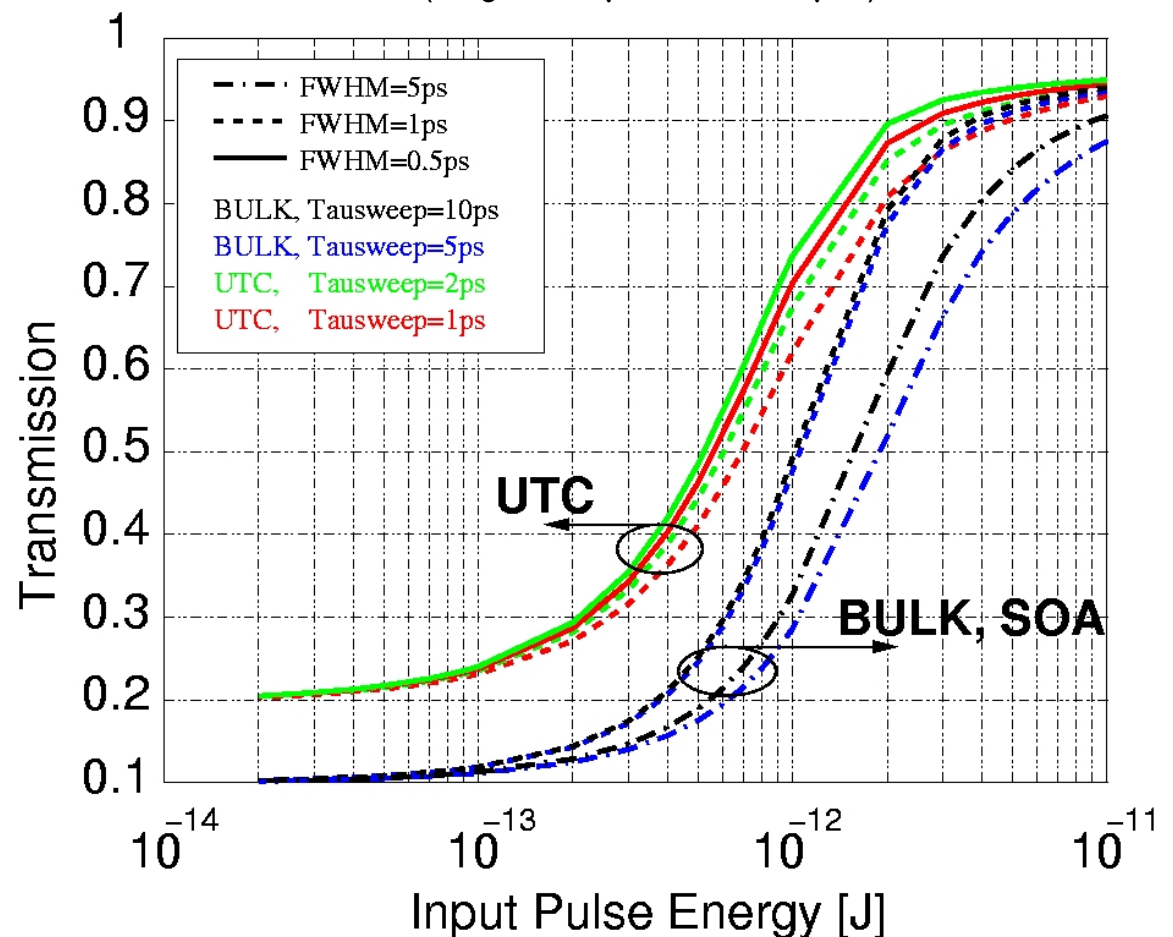
if $\tau_{pulse} \ll \tau_{sweep,abs}$

transmission increase is
determined only by $E_{Sat,N,abs}$

⇒ mode-centering

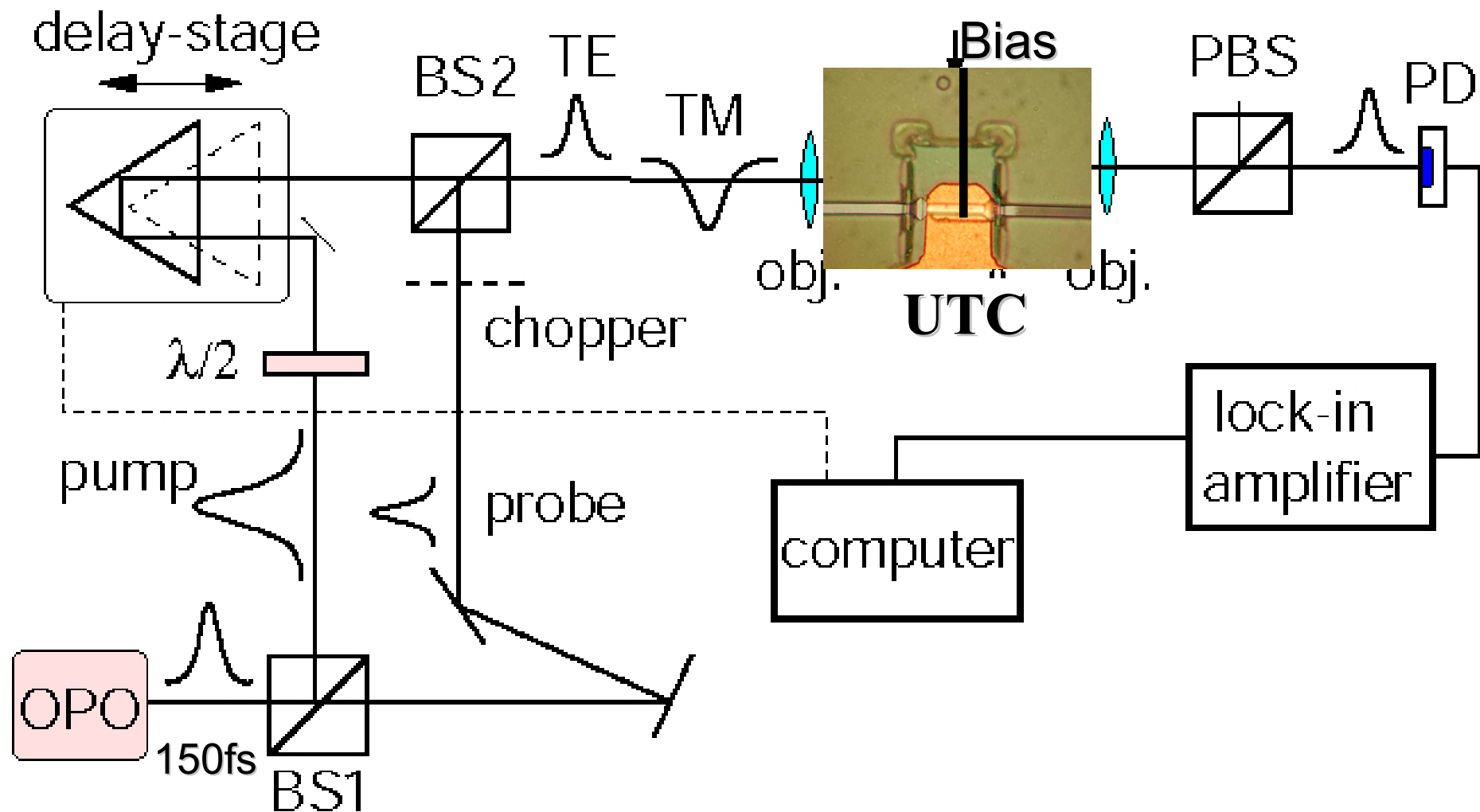
⇒ absorber material

E_{sat} : UTC ↔ SOA:
(length: 30μm 30μm)



UTC – Absorber Measurement

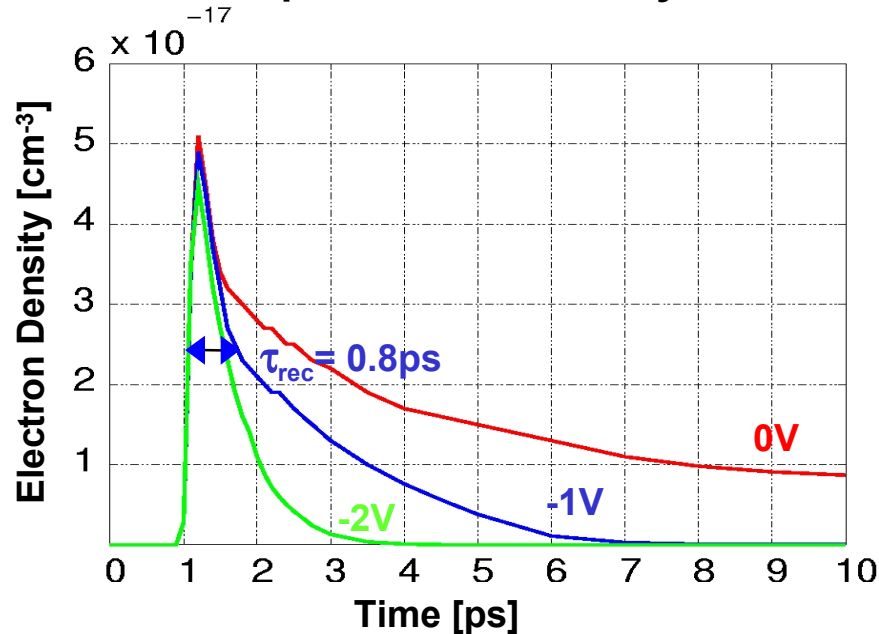
Pump-Probe Set-Up:



UTC – Absorber Measurement

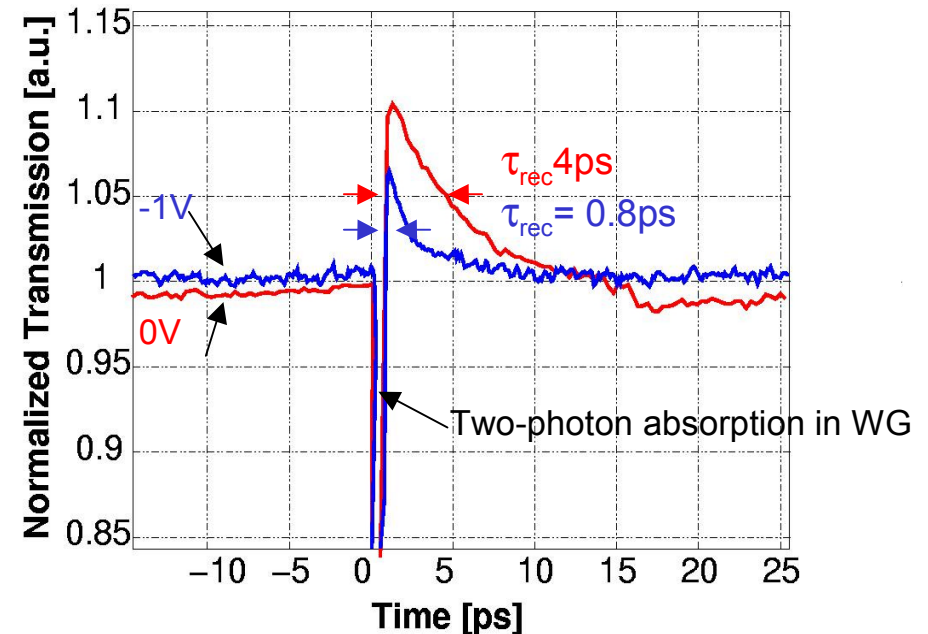
Simulation:

UTC Absorption and carrier dynamics

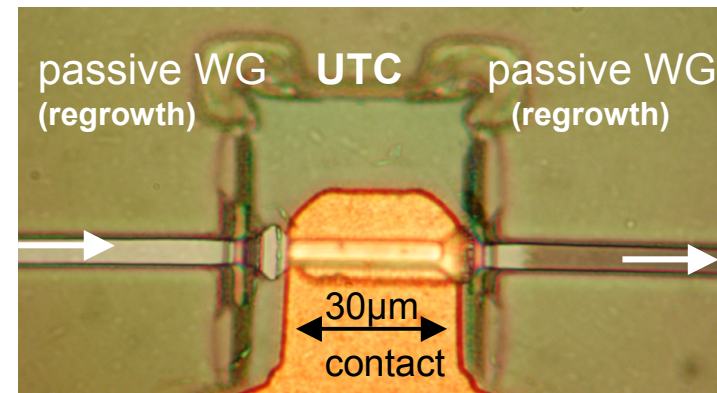


Measurement:

Pump-Probe Transmission



Fabricated UTC with passive WG:



Goals for UTC-Design reached:

- ➔ Carrier Sweep Time $\tau_{\text{sweep}} \sim 1\text{ps}$
- ➔ Good agreement simulation/measurement

Conclusions

Design:

- Identification of absorption recovery time as limiting factor for $< 1\text{ps}$ pulses
- Uni-Traveling-Carrier structure proposed and modeled
 - absorption recovery $< 1\text{ps}$
 - sweep out $< 5\text{ps}$
 - $E_{\text{sat}} \sim < 800\text{fJ}$ @ 1ps FWHM

Absorber Characterization:

- Pump-Probe demonstrates working UTC
- Good agreement between measured and simulated recovery time $\tau_{\text{rec}} \sim 0.8\text{ps}$

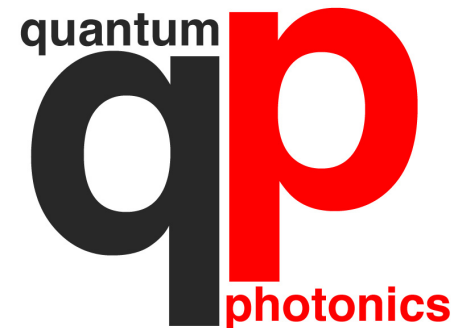
Outlook:

- Characterize saturation energy
- Optimize planar & vertical structures for MLLD

Acknowledgements



SCHWEIZERISCHER NATIONALFONDS
FONDS NATIONAL SUISSE
SWISS NATIONAL SCIENCE FOUNDATION



National Centre of Competence in Research

Alternative Technologies

- Ion Implantation

- No regrowth but facet damage
- Low reproducibility
- Electrons and holes recombine faster due to crystal defects

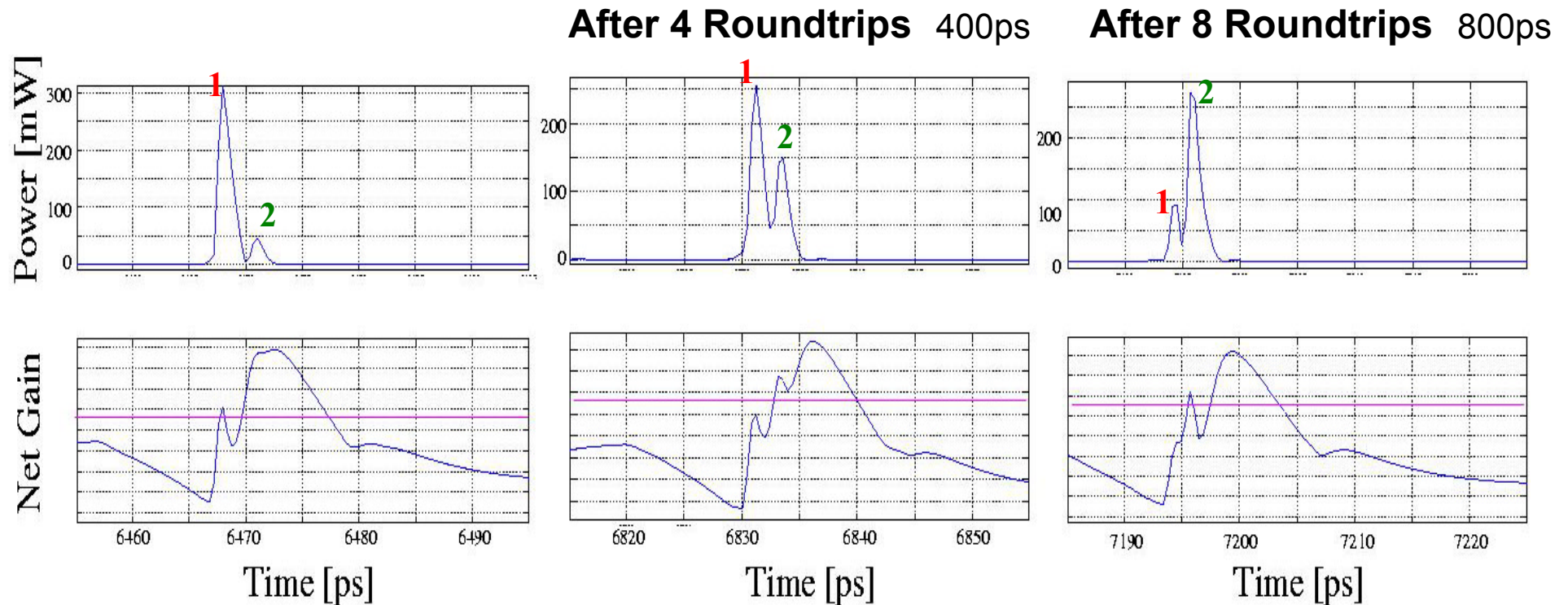
- Low-Temperature Growth

- Regrowth and difficult technology
- Electrons and holes recombine faster due to crystal defects

- Uni Traveling Carrier Structure

- Regrowth and transversal mode matching
- Carrier sweep-out

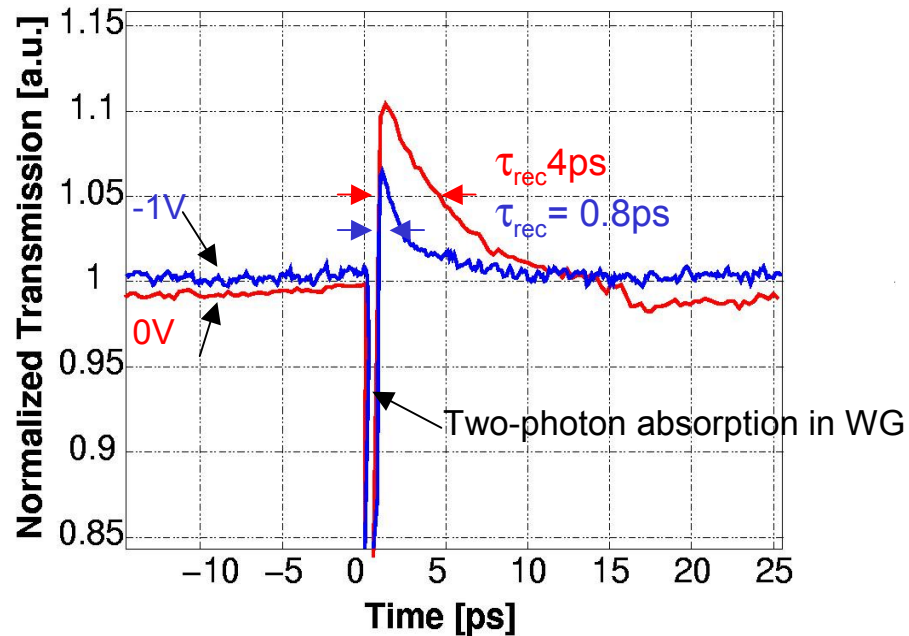
Pulse Build-Up



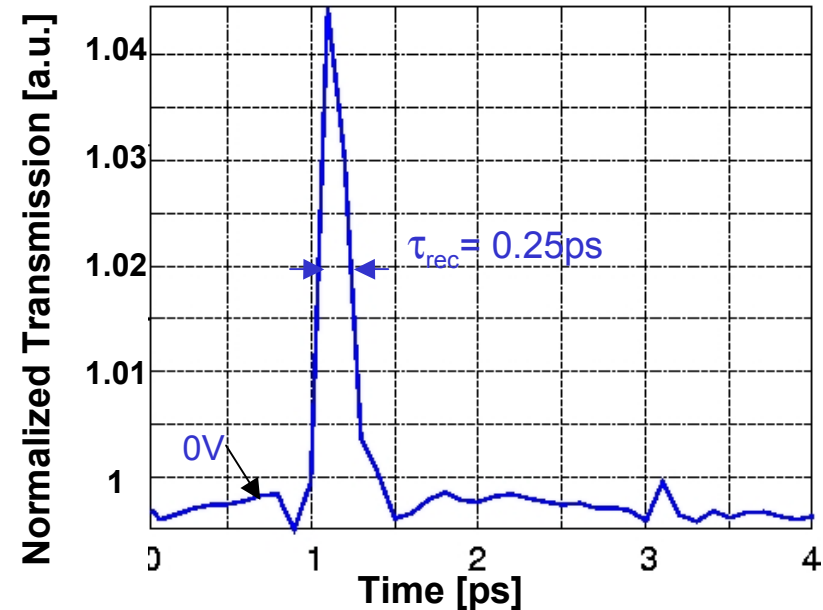
Due to fast intraband saturation and recovery of amplifier gain and slow recovery of the absorber: Pulse build-up after pulse.

Different Absorber Material

InGaAsP-Absorbing Layer:



InGaAs-Absorbing Layer:



Smaller Absorber Band-Gap:

Faster recovery but higher saturation energy due to spectral hole burning and carrier heating