INTERNATIONAL ATOMIC ENERGY AGENCY
UNITED NATIONS EDUCATIONAL, SCIENTIFIC AND CULTURAL ORGANIZATION
INTERNATIONAL CENTRE FOR THEORETICAL PHYSICS
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H4.SMR/842-13

Conference on
Ultrafast Transmission Systems in Optical Fibres

13 - 17 February 1995

Ultrafast Dynamics of Active Semiconductor Waveguides

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Ultrafast dynamics of active semiconductor waveguides

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Hørsholm, Denmark

Outline of talk

- ❒ Motivation
- ❒ Pump-and-probe measurements and theory
- ❒ Four-wave mixing
- ❒ Transport effects
- ❒ Conclusions

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Co-workers

Jannik Mark

Morten Willatzen

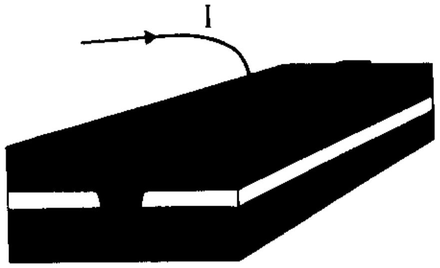
Michael Preisel

Alexander Uskov

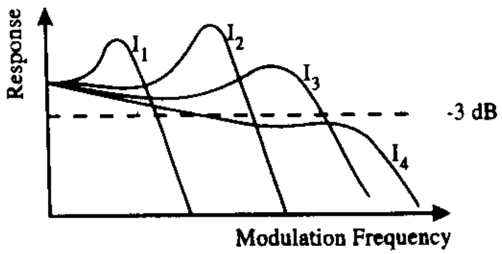
Antonio Mecozzi

Motivation

Electronic bottlenecks in optical communication systems
→ high-speed photonic components



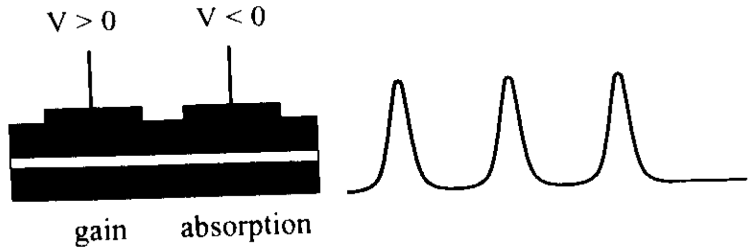
Laser diodes with large modulation bandwidth



Bandwidth limitation due to nonlinear gain

$$g = g_0(N)(1 - \varepsilon S)$$

Modelocked lasers for short-pulse generation



Optical processing at high bitrates

- ❒ optical amplification
- ❒ de-multiplexing
- ❒ frequency conversion
- ❒ synchronization/clock recovery
- ❒

→ Study of carrier dynamics on ultra-short time scales

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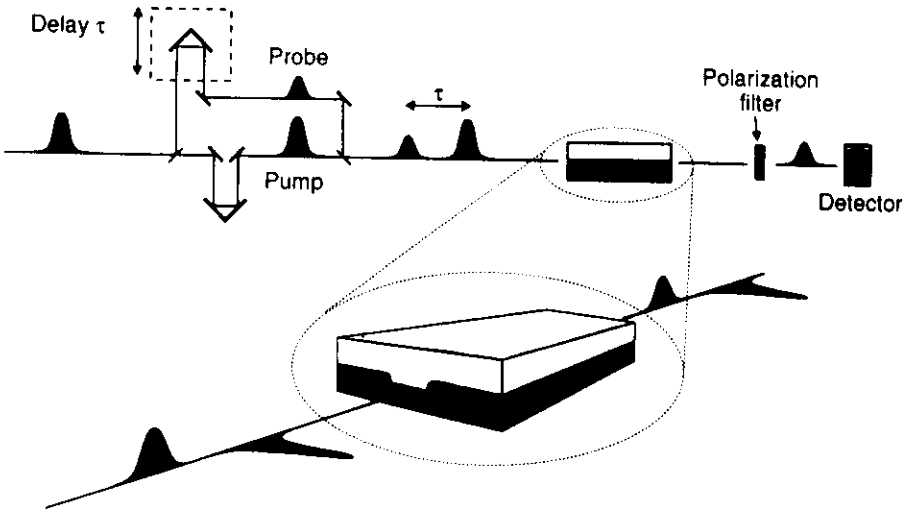
Pump-and-probe set-up



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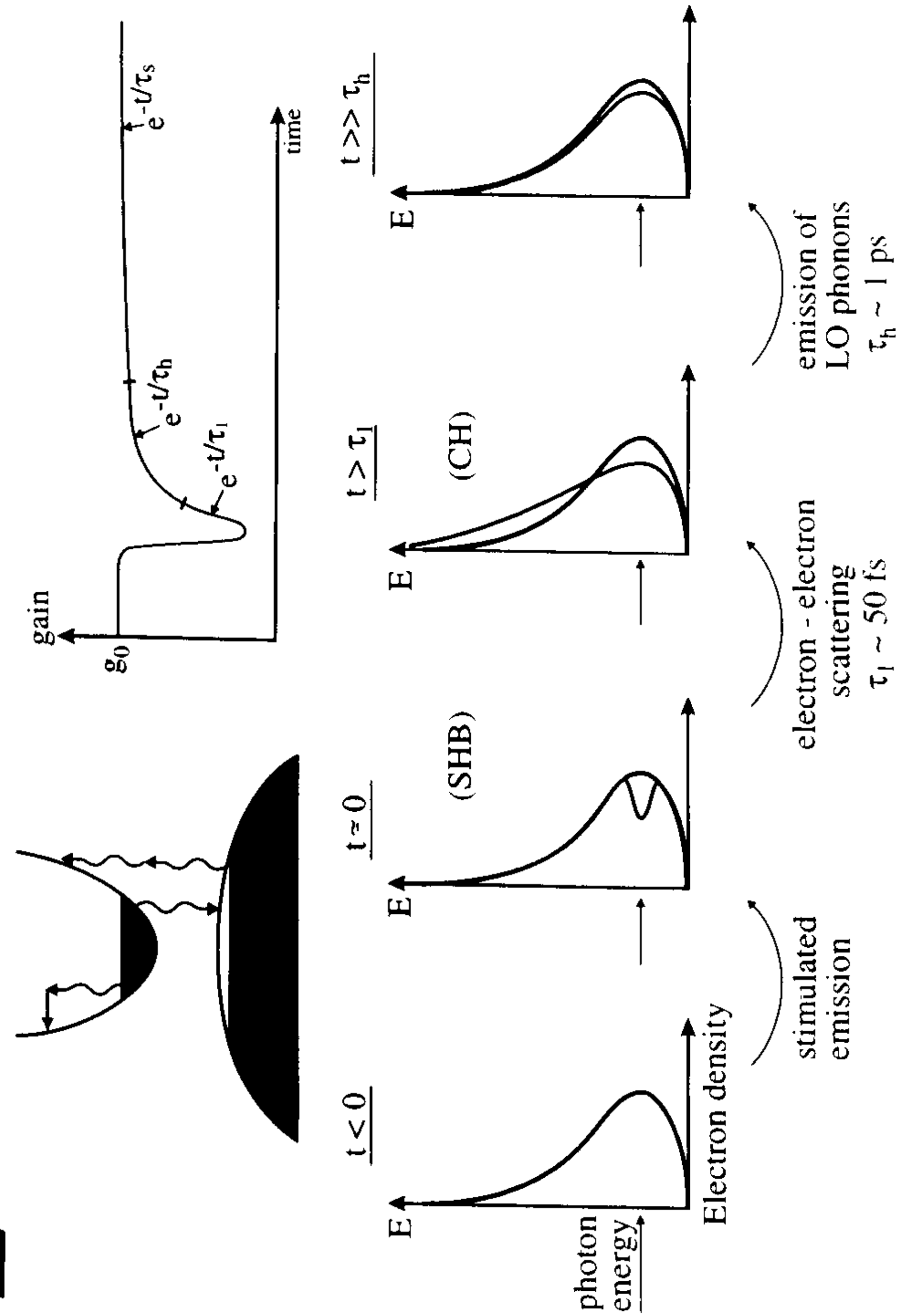
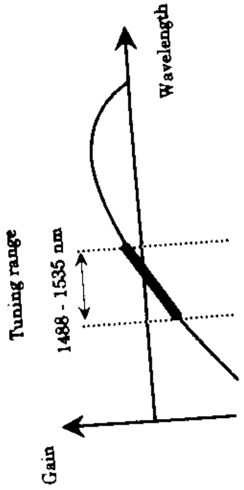
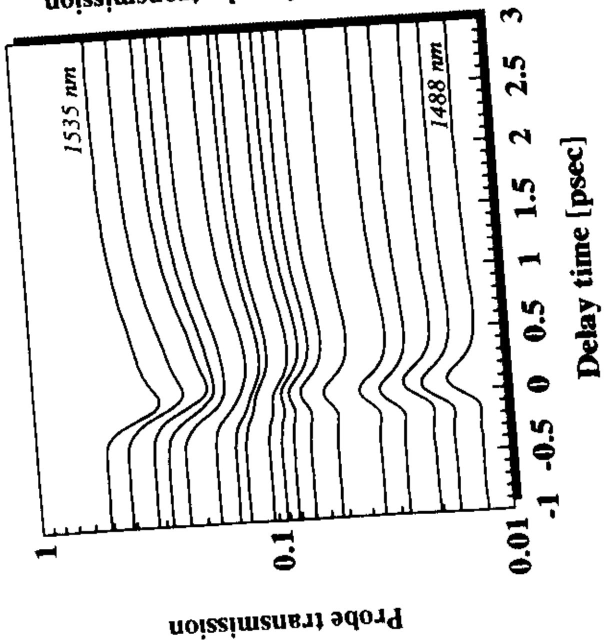
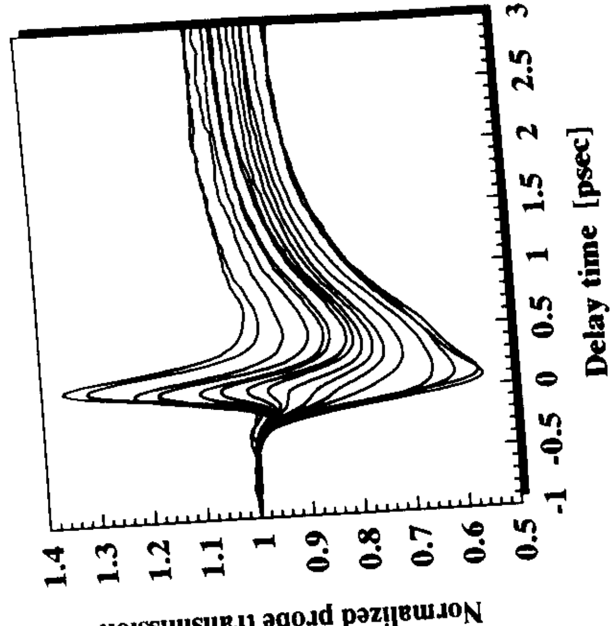


Pump-probe measurements on bulk amplifiers

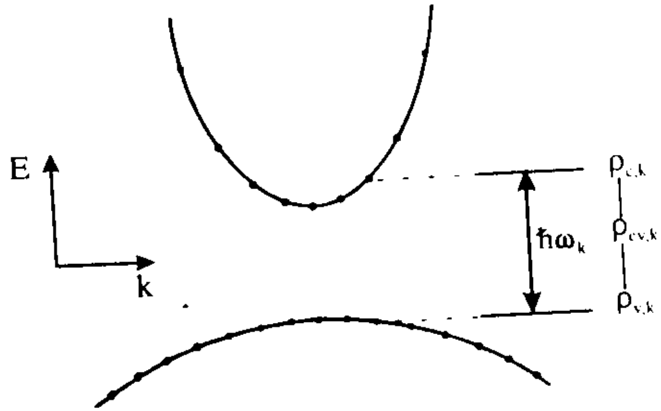
InGaAsP amplifier:
320 um
I = 10 mA
Pump energy 100 fJ, 125 fs
Probe energy 1 fJ







Density Matrix Equations



$$\dot{\rho}_{cv,k} = (-i\omega_k - \gamma_2)\rho_{cv,k} - \frac{i}{\hbar} d_k(\rho_{c,k} + \rho_{v,k} - 1)E(z,t)$$

$$\dot{\rho}_{\alpha,k} = -\frac{i}{\hbar}(d_k^*\rho_{cv,k} - c.c.)E(z,t) \underbrace{- \frac{\rho_{\alpha,k} - f_{\alpha,k}(t)}{\tau_1}}_{e-e} \underbrace{- \frac{\rho_{\alpha,k} - f^L_{\alpha,k}(t)}{\tau_h}}_{e-LO} \underbrace{- \frac{\rho_{\alpha,k} - f^{eq}_{\alpha,k}}{\tau_S}}_{recomb.}$$

$$\alpha = c, v$$

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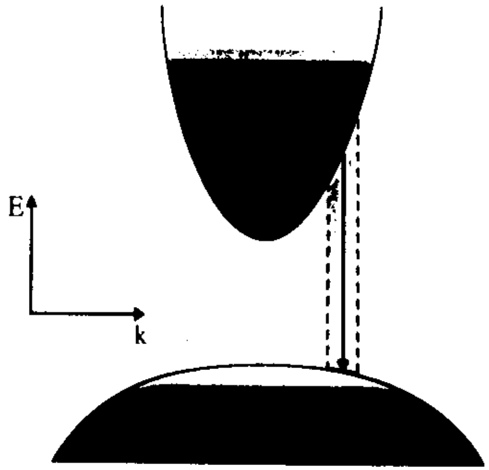
Simplified model

1) Eliminate polarization adiabatically; $\tau_2 << \tau_p$

$$|\rho_{cv,k}|^2 \propto \frac{|\rho_{c,k}+\rho_{v,k}-1|^2}{(\omega_0-\omega_k)^2+\gamma_2^2}|A(z,t)|^2$$



2) Consider "moments" of the distribution

$N = \sum_k \rho_{\alpha,k}$; carrier density, $\alpha = c, v$

$U_\alpha = \sum_k E_{\alpha,k}\rho_{\alpha,k}$; energy density

$n_\alpha = \sum_{k\in OPT} \rho_{\alpha,k}$; local carrier density

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Rate equations

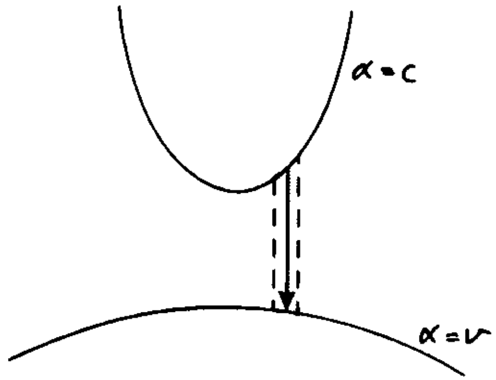
$$\frac{\partial N}{\partial t} = \frac{I}{eV} - \frac{N}{\tau_S} - v_g g S$$

$$\frac{\partial U_\alpha}{\partial t} = (\beta_\alpha \hbar\omega_0 - gE_\alpha)v_g S - \frac{U_\alpha - U_{L,\alpha}}{\tau_{h\alpha}}$$

$$\frac{\partial n_\alpha}{\partial t} = -\frac{n_\alpha - \bar{n}_\alpha}{\tau_{1\alpha}} - v_g g S$$

$$g = \frac{1}{v_g} a_N (n_c + n_v - N_0)$$

$$\bar{n}_\alpha = N_0 f(E_\alpha; N, U_\alpha)$$



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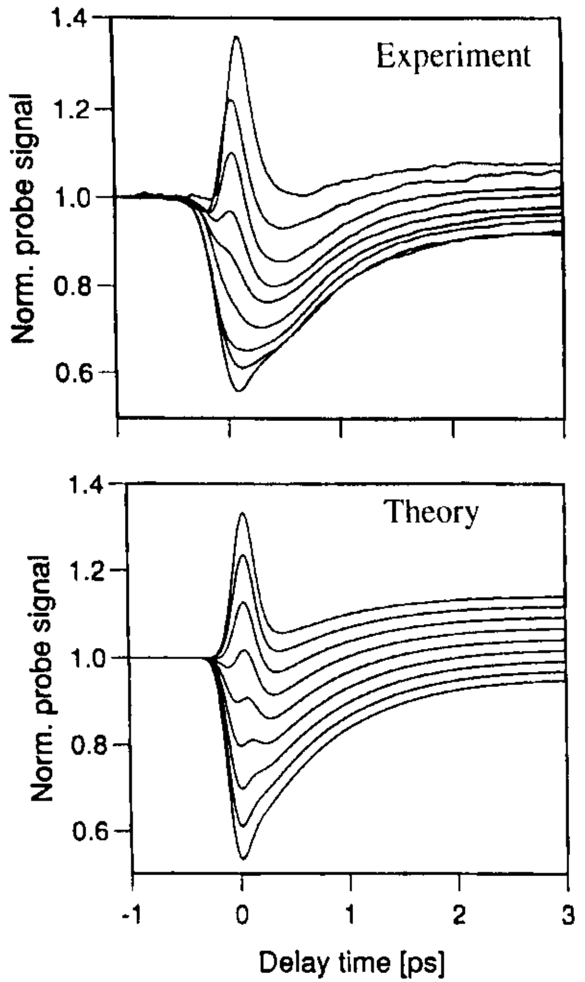
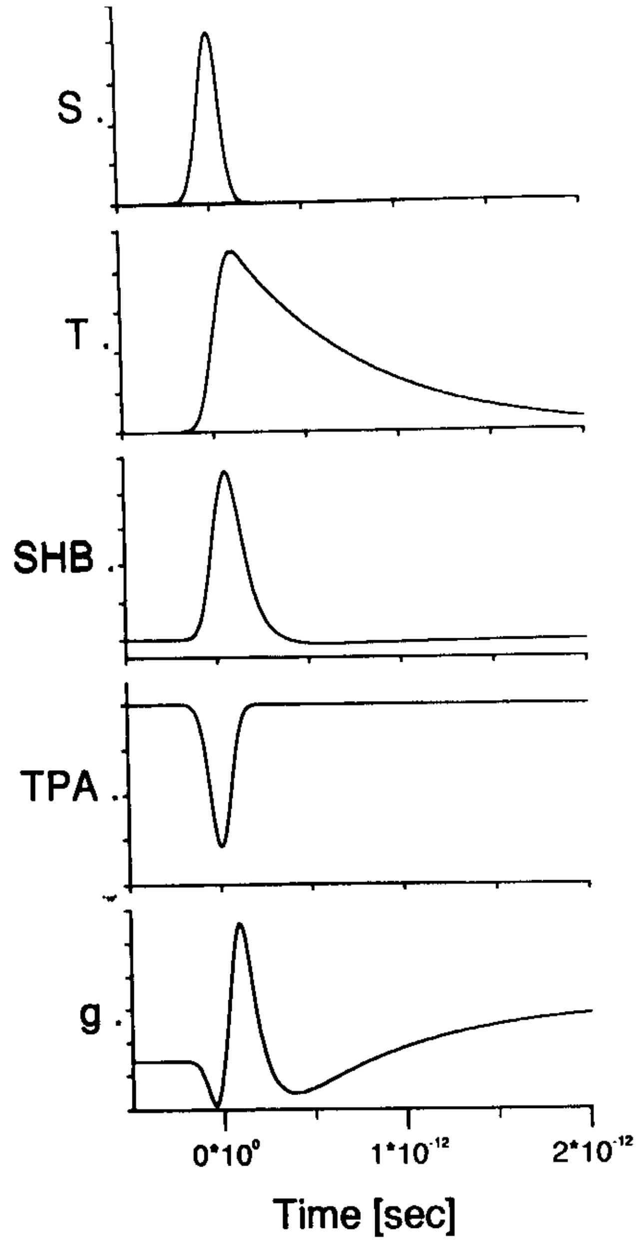
Comparison of experiment and theory
(InGaAsP bulk amplifier, I = 10 mA)



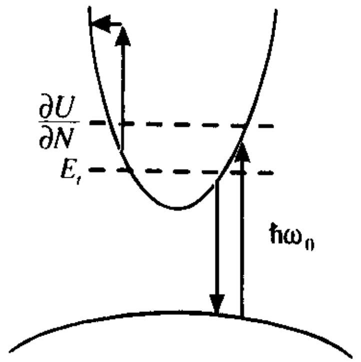
$\tau_{1c} = \tau_{1v} = 70$ fs

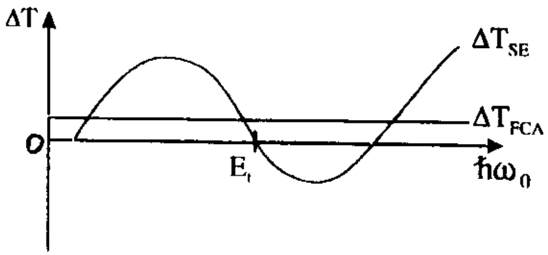
$\tau_{hc} = 0.7$ ps, $\tau_{hv} = 0.25$ ps

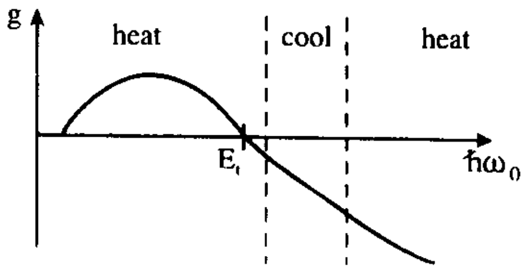


Carrier heating

$$\Delta T \propto \left(\frac{\partial U}{\partial N} - E_l\right) gS + \alpha_{FCA} N \hbar\omega_0 S$$

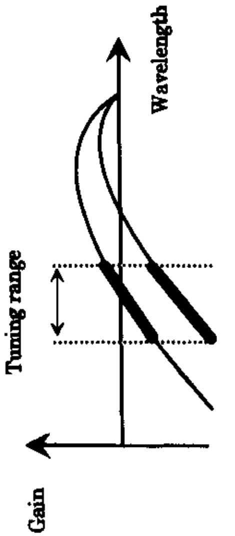


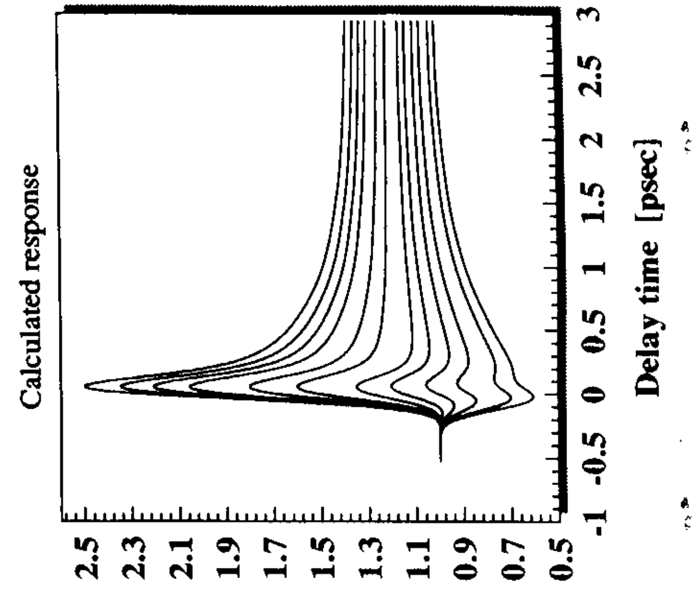


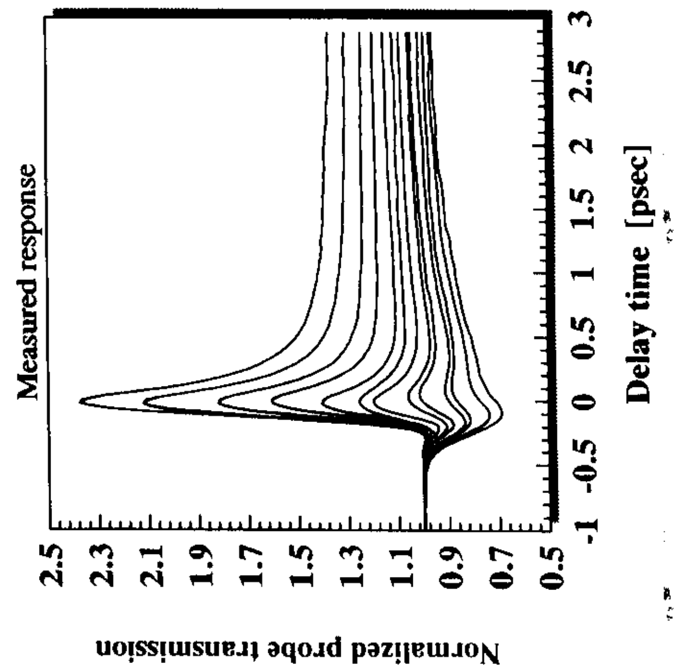


Pump-probe response measurements - MQW amplifier

InGaAsP/InP MQW amplifier:
2 x 80 Å well's
745 Å SCH width







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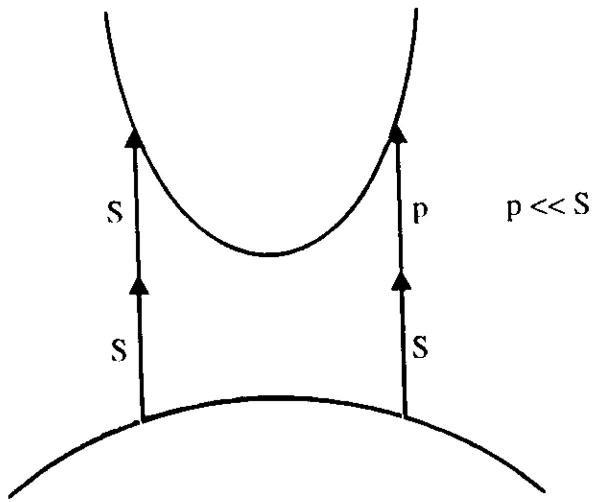
Two-photon absorption



TPA: $\beta_2 (S+p)^2 = \beta_2 S^2 + 2\beta_2 Sp + \beta_2 p^2$

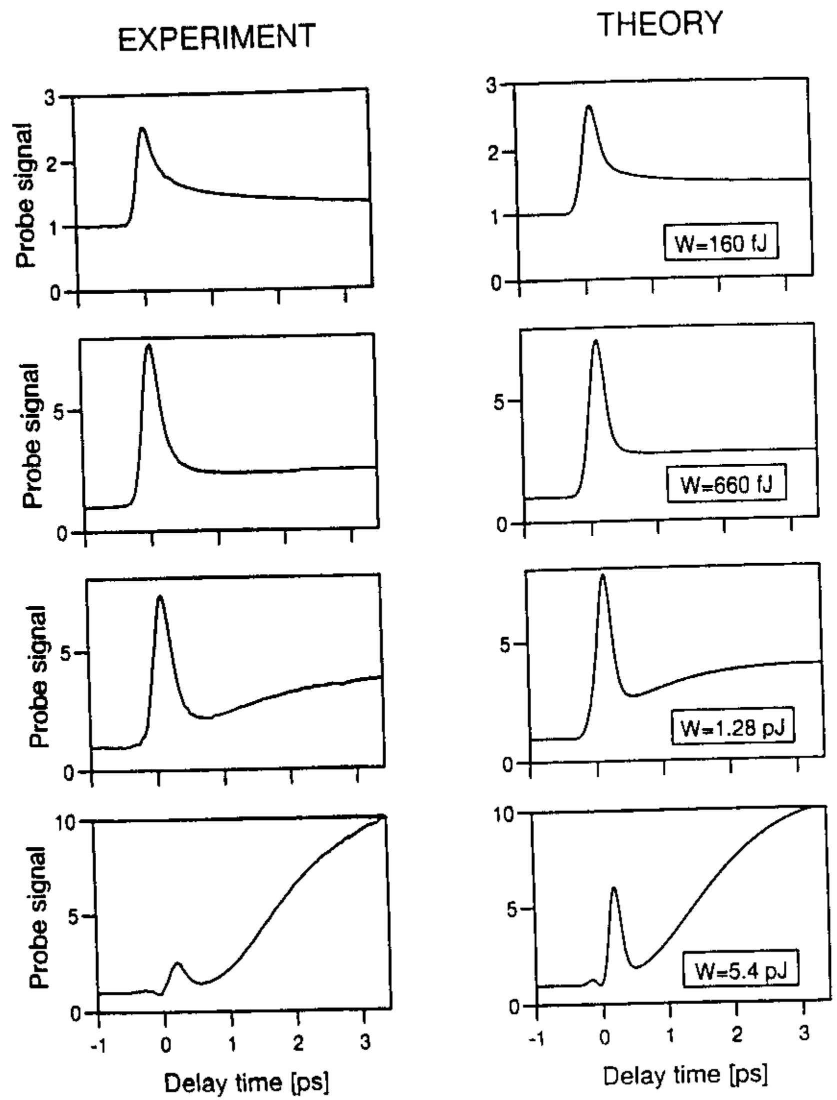
$$\frac{\partial S}{\partial z} + \frac{1}{v_g}\frac{\partial S}{\partial t} = \ldots\ldots\ldots -\beta_2 S^2$$

$$\frac{\partial p}{\partial z} + \frac{1}{v_g}\frac{\partial p}{\partial t} = \ldots\ldots\ldots -2\beta_2 Sp$$

$$\frac{\partial N}{\partial t} = \ldots\ldots\ldots + \frac{\Gamma_2}{\Gamma} v_g \beta_2 S^2$$

$$\frac{\partial U}{\partial t} = \ldots\ldots\ldots + \frac{\Gamma_2}{\Gamma} v_g \beta_2 E_2 S^2$$

Strong pump results



APL 64, 2206 (Apr. '94)

Nonlinear gain in laser diodes

$$\frac{dS}{dt}, \frac{dN}{dt}, \frac{dU}{dt}, \frac{dn}{dt}$$
$$g = g(n; N, U)$$

$\Downarrow$ Adiabatical elimination of n, U for time scales $\gg \tau_1, \tau_h$

$$\frac{dS}{dt}, \frac{dN}{dt}$$
$$g = g_0(N)(1-\varepsilon S)$$
$$\varepsilon = \varepsilon_{CH} + \varepsilon_{SHB}$$

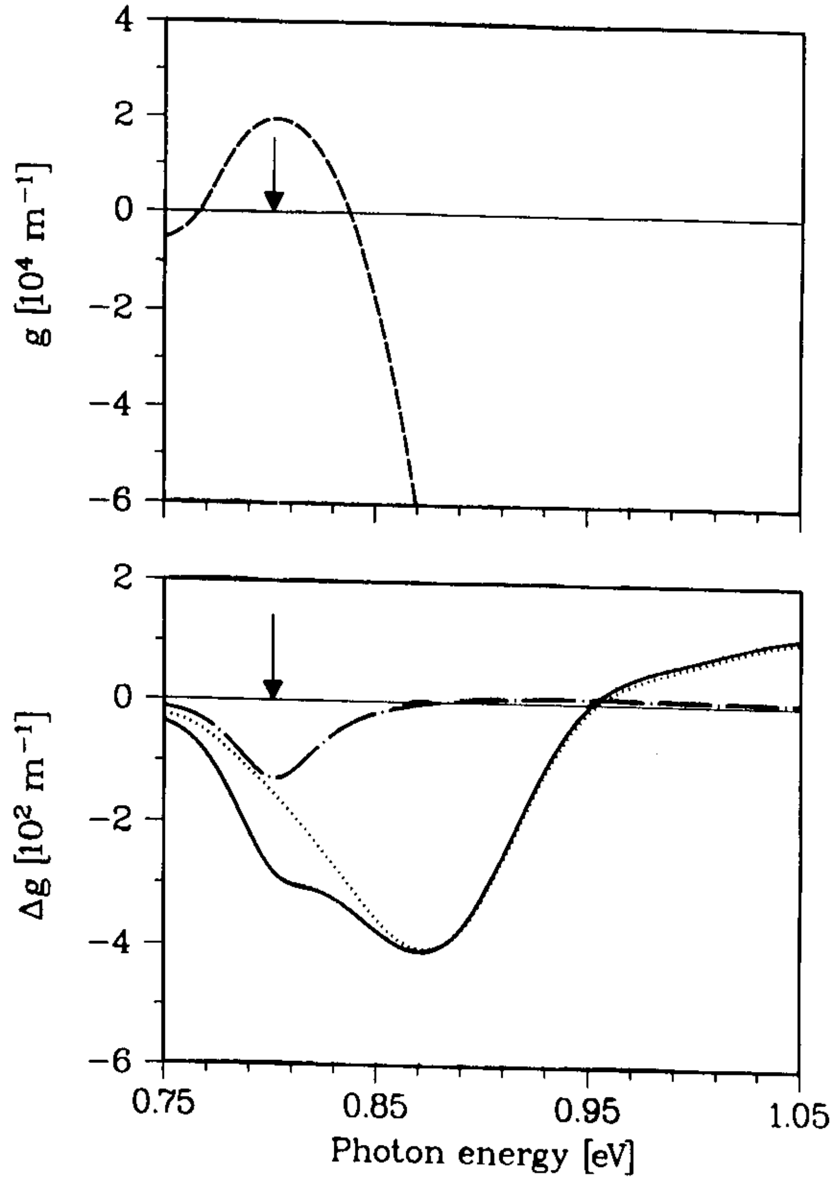
Typical example (1.55 μm bulk InGaAsP):

$\varepsilon_{CH} \cong 0.8 \cdot 10^{-23}\,\mathrm{m}^3$ ($\tau_h = 0.5$ ps)

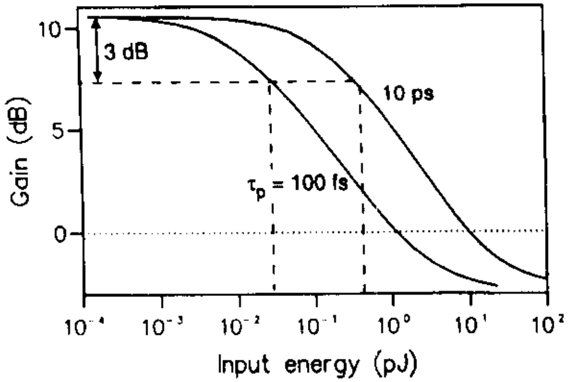
$\varepsilon_{SHB} \cong 0.7 \cdot 10^{-23}\,\mathrm{m}^3$ ($\tau_1 = 50$ fs)

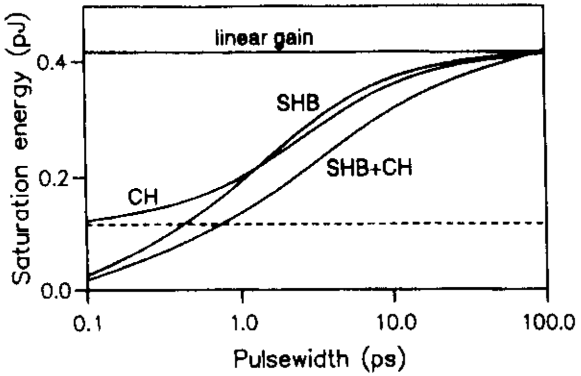
$\varepsilon \cong 1.5 \cdot 10^{-23}\,\mathrm{m}^3$

CW gain suppression (1.55 μm InGaAsP)



Short pulse gain saturation





$$\tau_p >> \tau_x \Rightarrow \Delta g_x \approx -\varepsilon_x g_0 S$$

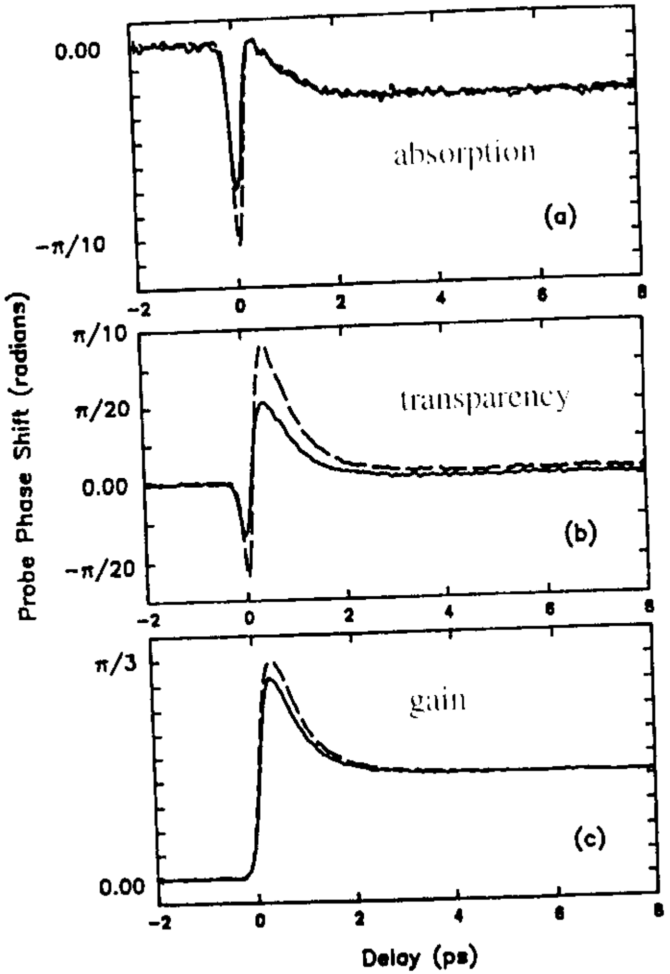
$$S_{\text{peak}} \cong E_p / \tau_p$$

$$\tau_p << \tau_x \Rightarrow \Delta g_x \approx -g_x' \int S(t)dt$$

Photon. Technol. lett., vol. 4, 443 (1992).

Refractive index dynamics

(Bulk InGaAsP amplifier)



K. L. Hall, MIT, 1993

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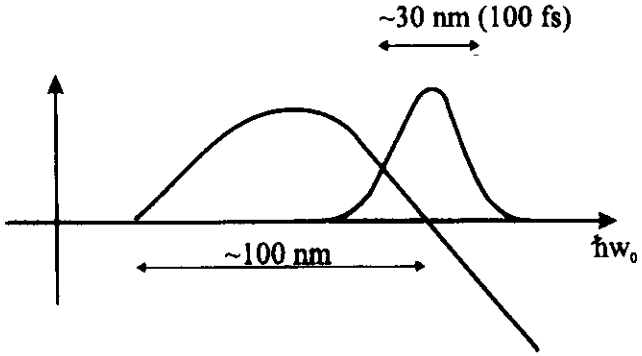
Spectral effects in pump-and-probe measurements



$$\Delta n(t) \rightarrow \Delta\omega(t) \rightarrow \Delta g(t) = \frac{\partial g}{\partial \omega}\Delta\omega(t)$$

Gain and index dynamics mix up in measurements!

"Unified" treatment: Perturbation analysis of DME and propagation equations.

J. Mark, A. Mecozzi
APL, 65, 1736
(1994)

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Pump-probe response function

$$\underbrace{\Delta V_R(\tau)}_{\text{gain}} + \underbrace{i\Delta V_I(\tau)}_{\text{index}} = K\int H(t')G^{(2)}(\tau - t')dt'$$

Waveguide response function:

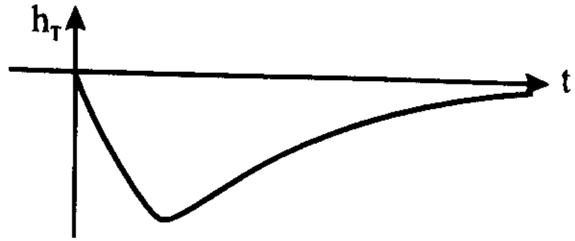
$$H(t) = \frac{e^{2g_0L} - e^{g_0L}}{g_0}\left[1 + i\xi(L)\frac{\partial g}{\partial\omega}\frac{\partial}{\partial t}\right]h(t)$$

Material response function:

$$h(t) = h_N(t) + h_T(t) + h_{SHB}(t) + h_{TPA}(t)$$

Example:

$$h_T(t) \propto -\varepsilon_T(1 - i\alpha_T)\left[e^{-t/\tau_h} - e^{-t/\tau_1}\right]u(t)$$



Relation between gain and refractive index changes

$$\alpha = \frac{\Delta\chi_R}{\Delta\chi_I}$$

Ex: Usual linewidth enhancement factor

$$\alpha_N = \frac{\Delta\chi_R/\Delta N}{\Delta\chi_I/\Delta N}$$

$$= -\frac{4\pi}{\lambda}\frac{\partial n/\partial N}{\partial g/\partial N} \cong 3-7$$

Similarly

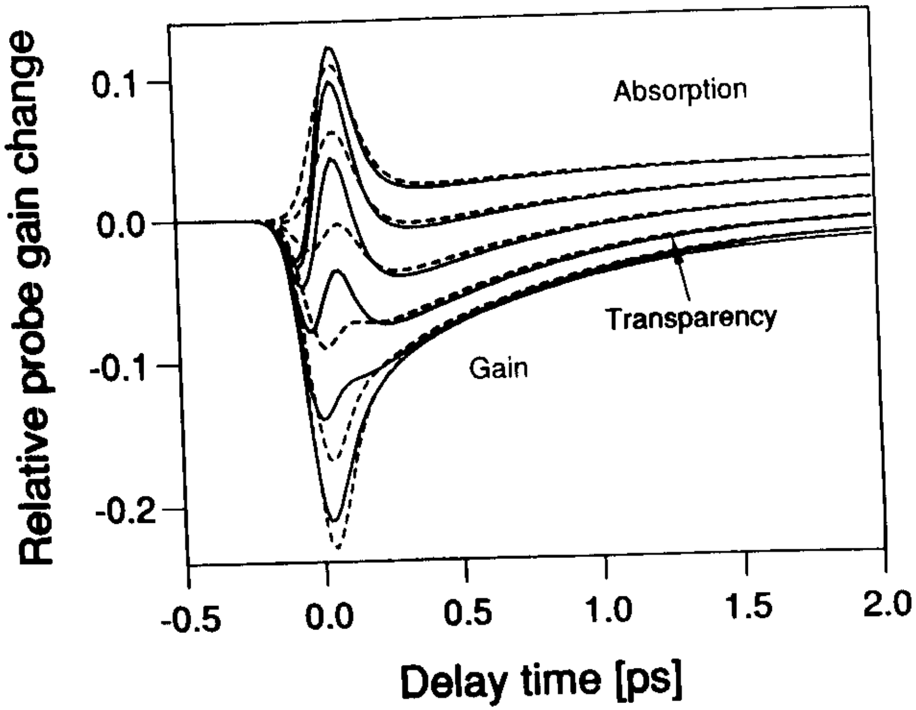
$$\alpha_T \cong 1-4$$

$$\alpha_{SHB} \cong 0.1$$

$$\alpha_{TPA} \cong ? \qquad \text{(-3 for bulk InGaAsP)}$$

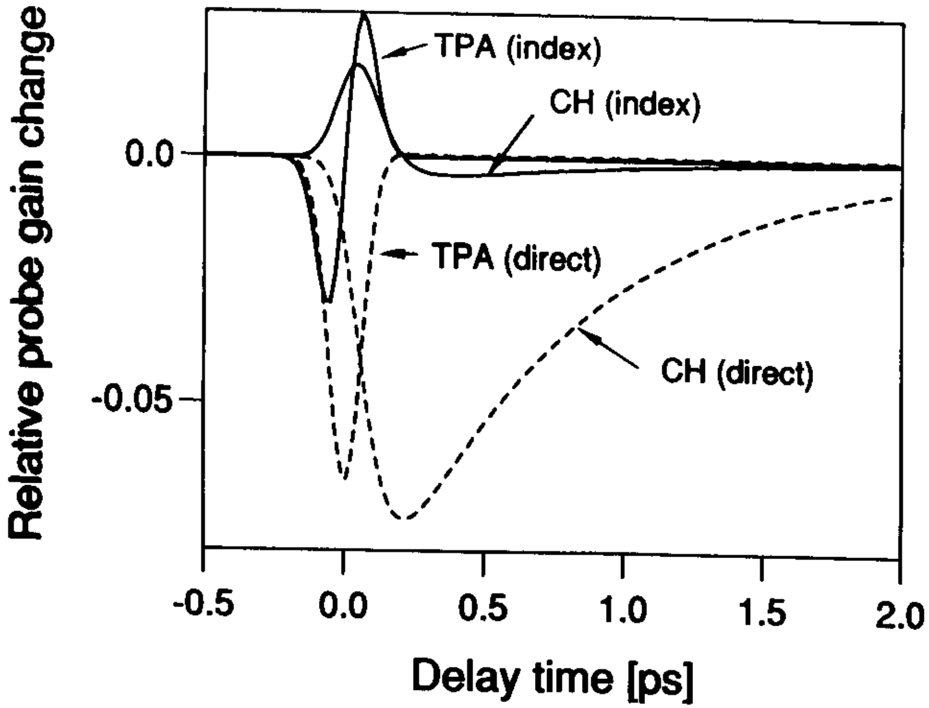
Calculated pump-probe responses; gain

$\hbar\omega_0 = 0.79$ eV, .., 0.82 eV; $N = 1 \cdot 10^{24}\mathrm{m}^{-3}$; $\tau_p = 100$ fs



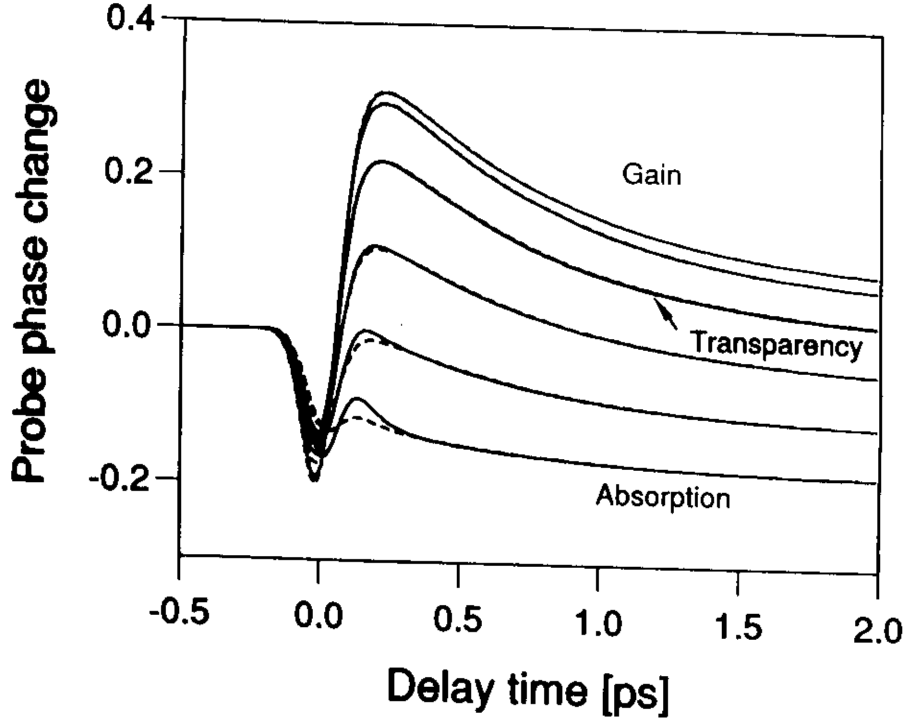
Contributions to probe transmission at transparency

$\hbar\omega_0 = 0.800$ eV; $N = 1 \cdot 10^{24} \text{m}^{-3}$; $\tau_p = 100$ fs

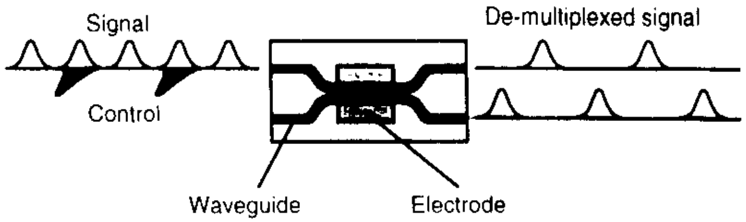


Calculated pump-probe responses; phase

$\hbar\omega_0 = 0.79$ eV, .., 0.82 eV; $N = 1 \cdot 10^{24} \text{m}^{-3}$; $\tau_p = 100$ fs



Transparency switch



Bias at transparency:

$\Delta T \neq 0 \Rightarrow$ index change

$\Delta N = 0 \Rightarrow$ fast recovery

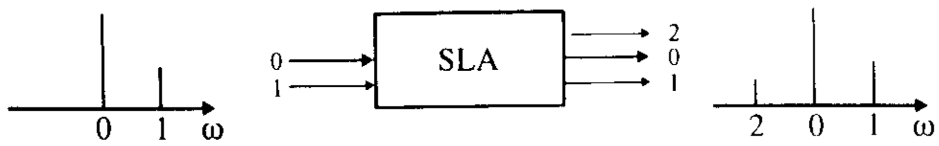
First results (Davies et al., BT Labs, 1993)

Nonlinear transmission characteristics;

15 ps pulses, 10 W peak power

~ 10 pJ for 1 ps pulses

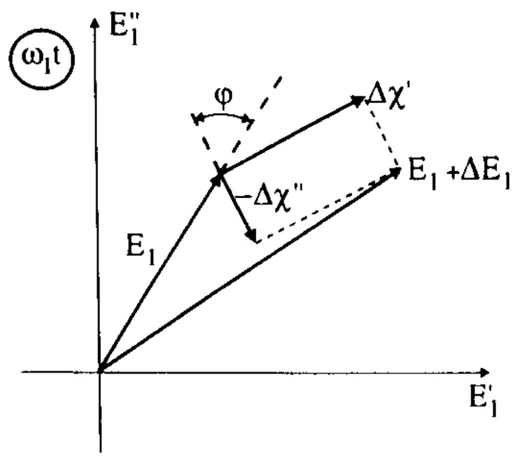
Wave mixing



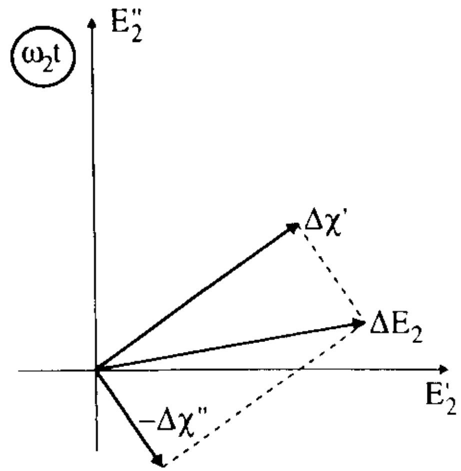
$$|E(t)|^2 = |E_0|^2 + E_0^* E_1 e^{-i\Omega t} + c.c.$$

$$\Rightarrow \chi(t) = \overline{\chi} + \Delta\chi e^{-i\Omega t - i\varphi} + c.c.$$

$$\Rightarrow \Delta E \propto i\chi(t)\ E(t)\,\Delta z$$



probe
("Bogatov effect")



conjugate

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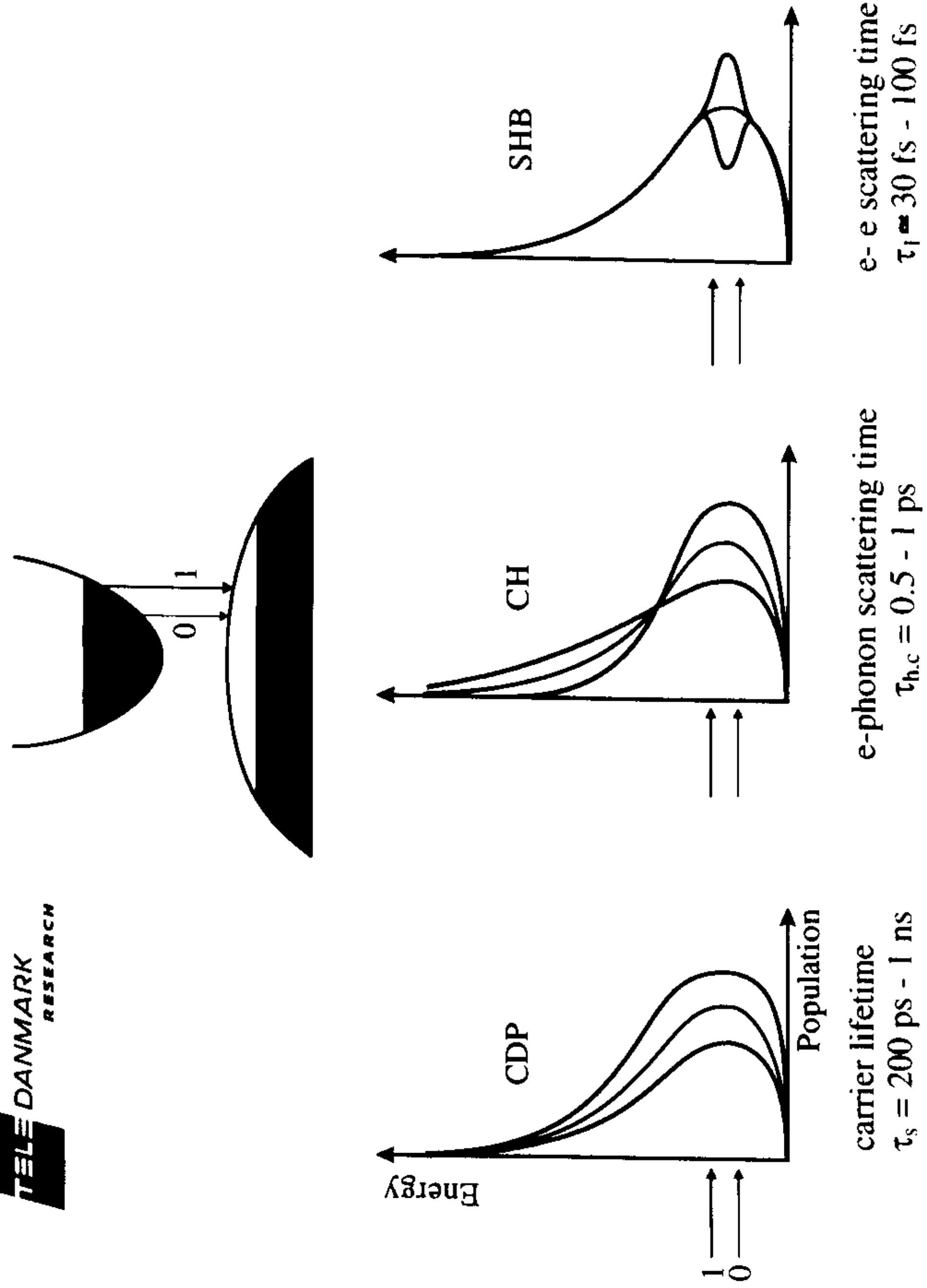

jme107-8

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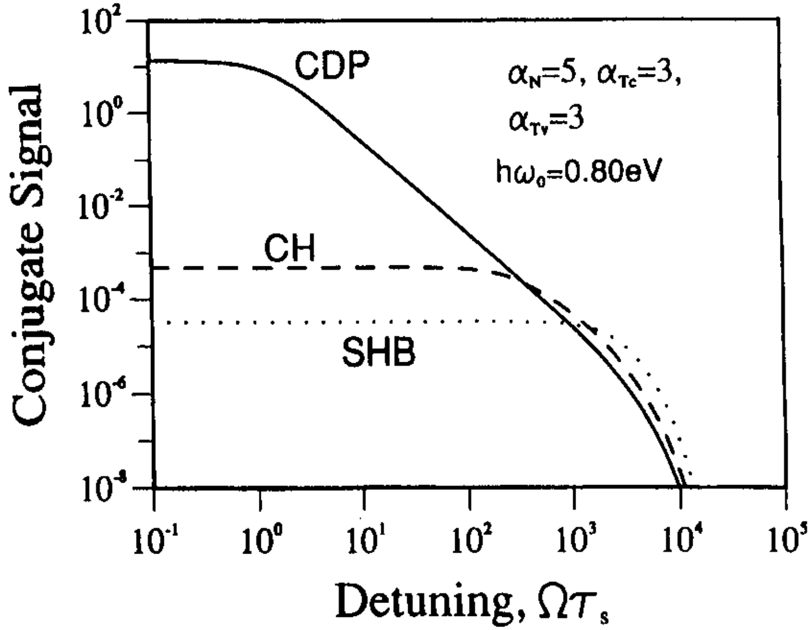
Amplitude of $\chi^{(3)}$



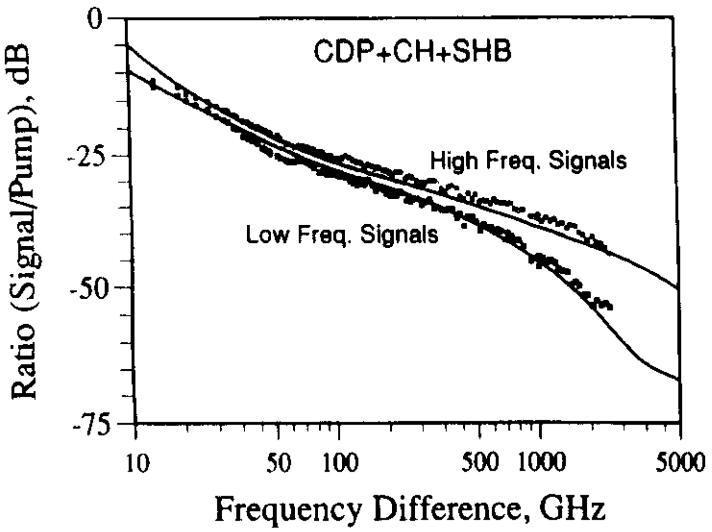
$\tau_S = 200$ ps ; $\frac{1}{2\pi\tau_S} = 800$ MHz

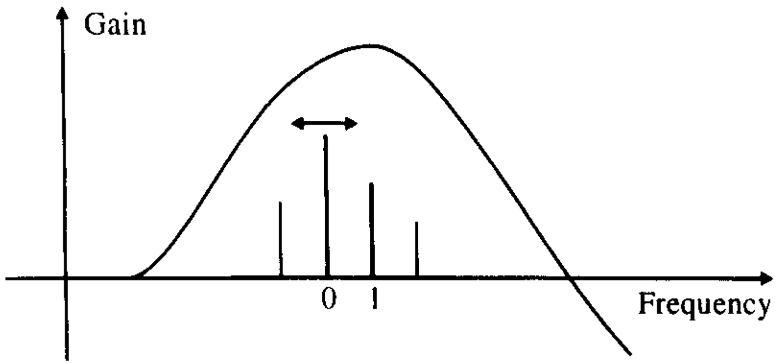
$\tau_{h,c} = 650$ fs ; $\frac{1}{2\pi\tau_{h,c}} = 245$ GHz

$\tau_1 = \tau_2 = 50$ fs; $\frac{1}{2\pi\tau_1} = 3.2$ THz

JQE. 30.

Experiment and theory





$P_0 = 0.25$ mW (tunable ECL)
$P_1 = 0.10$ mW (fixed DFB)

A. Ushor, J. Mark, J. Mark,
M. Tatham, G. Sherlock,

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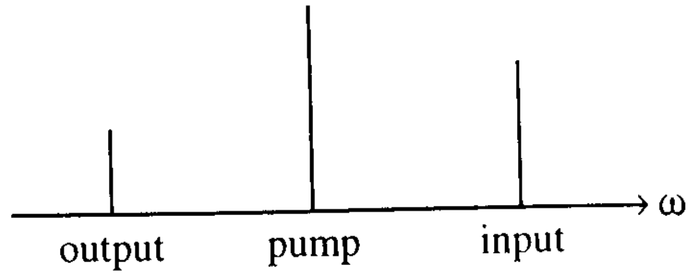
Applications of four-wave mixing in laser amplifiers



- ❒ Frequency conversion

  18 Gb/s over 15 nm (2 THz)

  [Schnabel, HHI, 1993]

- ❒ Dispersion compensation

  Mid-span spectral inversion by FWM

  Transmission of 10 Gb/s over 200 km

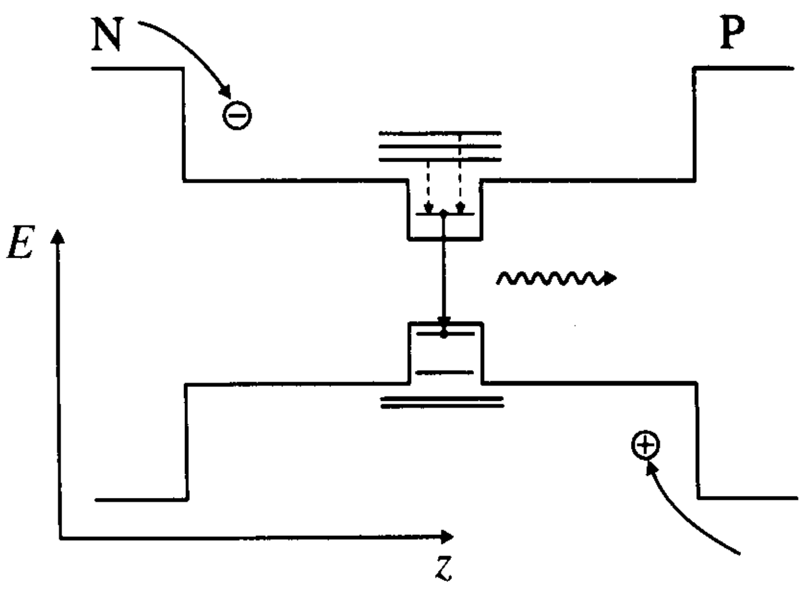
  [Tatham, BT Labs, ECOC '94]

- ❒ All-optical de-multiplexing

  Error-free de-multiplexing of 100 Gb/s signal (16 x 6.3 Gb/s)

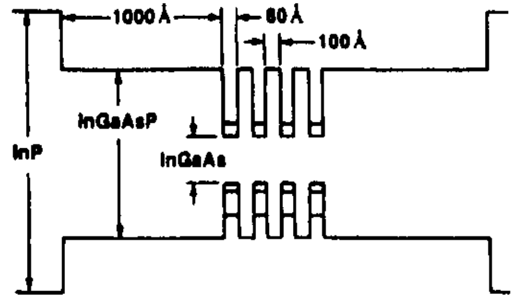
  [Kawanishi, NTT, 1994]

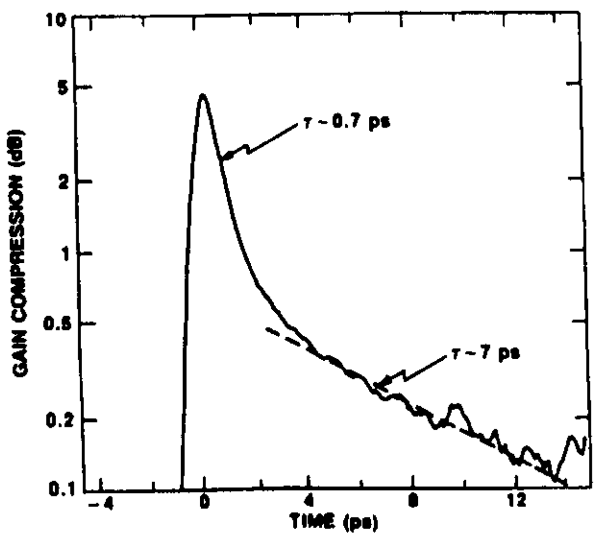
Transport and capture in QW devices



- Quantum mechanical capture
- Classical transport

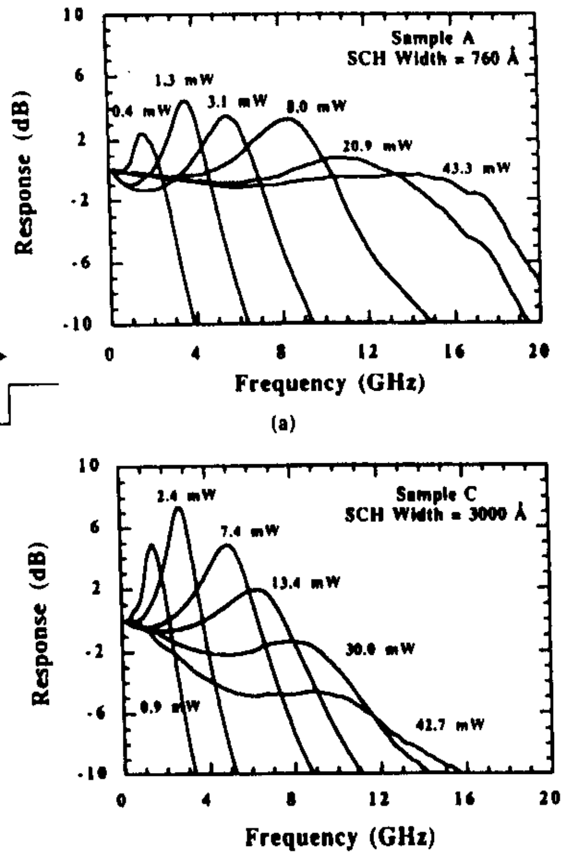
Pump-probe on MQW amplifier



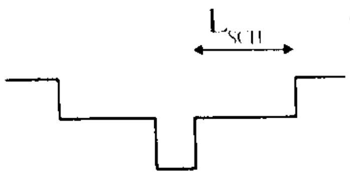


G. Eisenstein et al., APL, Jan. '91

Modulation response of QW lasers



(a) (b)

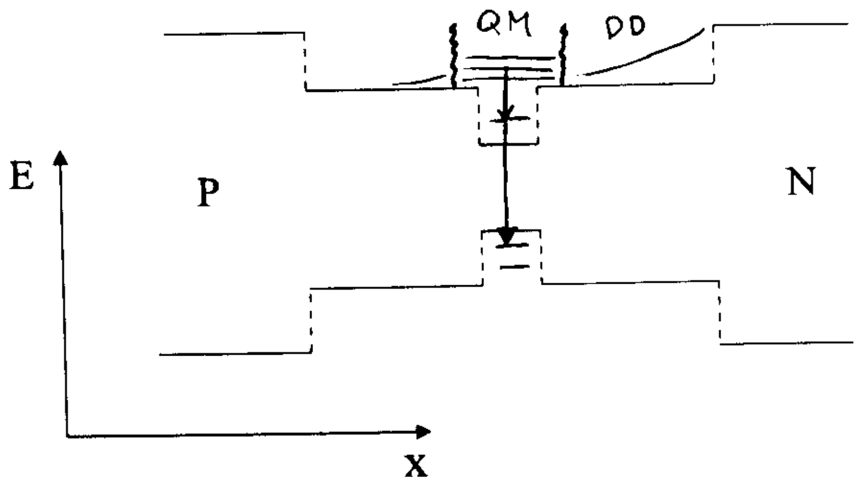


Nagarajan et al., JQE, Oct. '92

- ❒ Short SCH ⇒ enhanced damping of RO
- ❒ Long SCH ⇒ capacitive-like roll-off

Tessler et al., JQE, Oct. '92
(rate equation analysis)

Transport model for P-I-N heterostructure



Classical transport:

Drift-diffusion, Poisson's eq.

Boundary conditions at contacts

Rate eqs. for carrier capture

Quantum mechanical capture:

Boltzmann equation for carrier scattering processes

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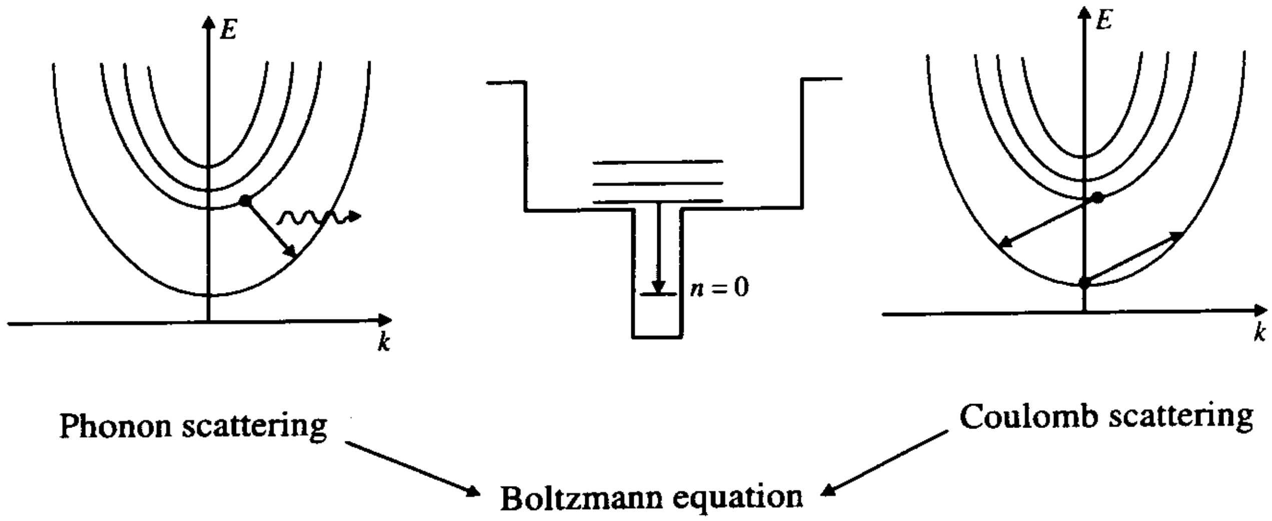
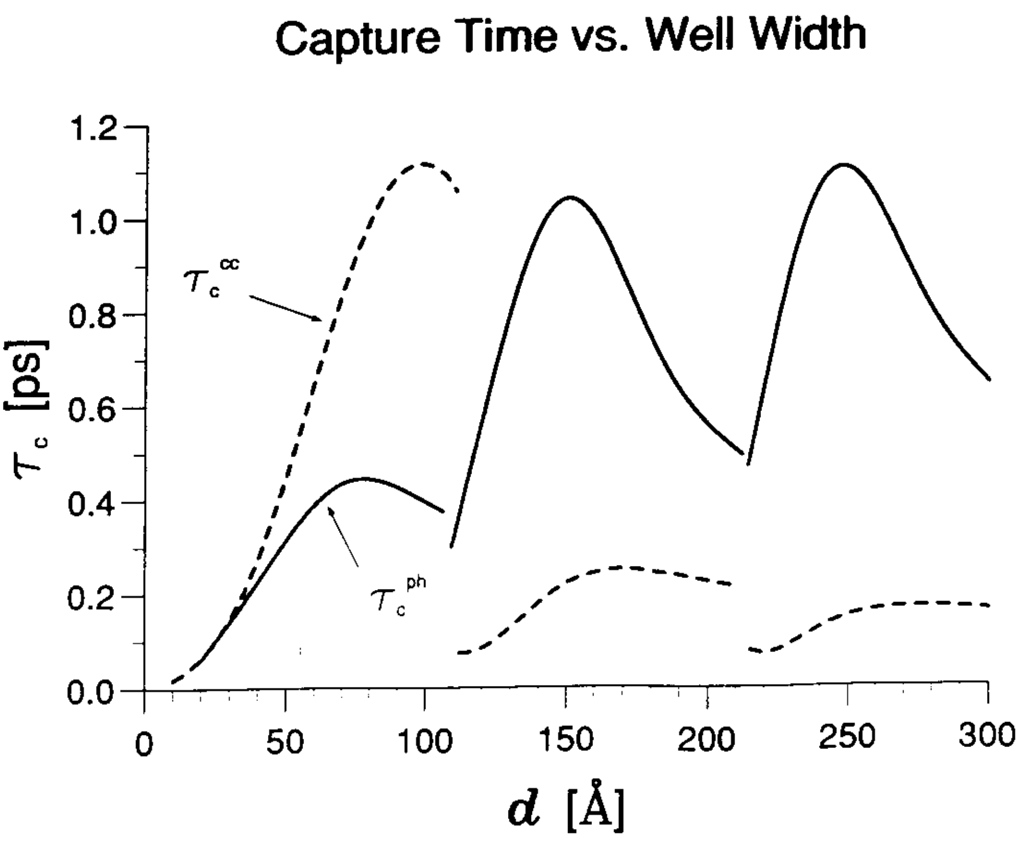


PRB, May '94
M. Preisel and J. Mørk, J.A.P., Aug. '94



TELE DANMARK RESEARCH

Summary

- Study of ultrafast carrier dynamics for
  - laser modulation
  - modelocking
  - photonic switching

- Dynamics of bulk devices explained by simple models for time-scales > 50 fs ($\Delta\omega$ < 3 THz)
  - Nonlinear gain
  - Small-signal response function
  - Strong pump excitation

- Further work needed to understand relative roles of intraband dynamics and capture/transport effects in QW devices