Gain Switched Laser Diodes for Laser Radars and 3D Laser Imaging

Presented by:

OSA Laser Systems Technical Group


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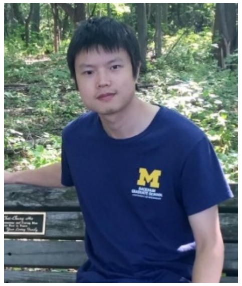

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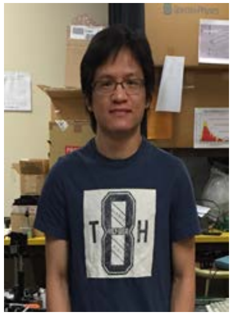

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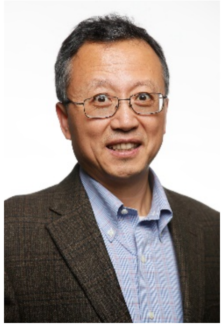

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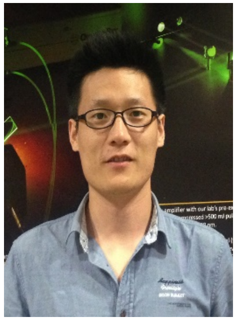

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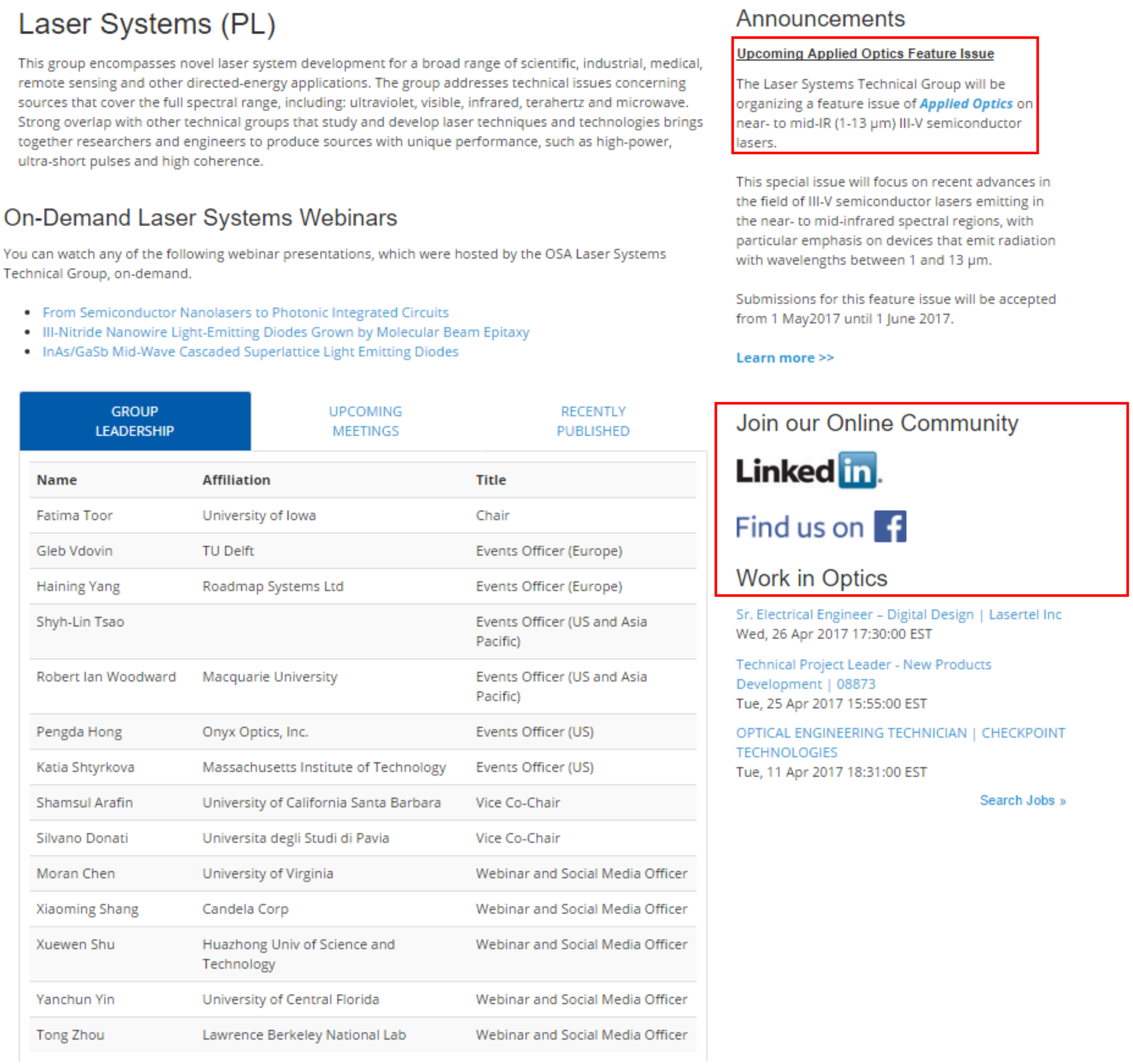

Laser Systems (PL)

This group encompasses novel laser system development for a broad range of scientific, industrial, medical, remote sensing and other directed-energy applications. The group addresses technical issues concerning sources that cover the full spectral range, including: ultraviolet, visible, infrared, terahertz and microwave. Strong overlap with other technical groups that study and develop laser techniques and technologies brings together researchers and engineers to produce sources with unique performance, such as high-power, ultra-short pulses and high coherence.

On-Demand Laser Systems Webinars

You can watch any of the following webinar presentations, which were hosted by the OSA Laser Systems Technical Group, on-demand.

- From Semiconductor Nanolasers to Photonic Integrated Circuits
- III-Nitride Nanowire Light-Emitting Diodes Grown by Molecular Beam Epitaxy
- InAs/GaSb Mid-Wave Cascaded Superlattice Light Emitting Diodes

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Announcements

Upcoming Applied Optics Feature Issue

The Laser Systems Technical Group will be organizing a feature issue of ***Applied Optics*** on near- to mid-IR (1-13 µm) III-V semiconductor lasers.

This special issue will focus on recent advances in the field of III-V semiconductor lasers emitting in the near- to mid-infrared spectral regions, with particular emphasis on devices that emit radiation with wavelengths between 1 and 13 µm.

Submissions for this feature issue will be accepted from 1 May2017 until 1 June 2017.

Learn more >>

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OSA Laser Systems Technical Group

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- LinkedIn site (global reach)
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Laser Systems Technical Group

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Shamsul Arafin · Moderator ··· 58m

Assistant Project Scientist at UC Santa Barbara

Webinar on Gain Switched Laser Diodes for Laser Radars and 3D Laser Imaging

https://cc.callinfo.com/r/143ugahu4lxnk&eom

Gain Switched Laser Diodes for Laser Radars and 3D Laser Imaging

Date: Thu, Oct 26, 2017, Time: 12:00 PM EDT, Host(s): OSA Technical Groups. Short (~ 100 ps) and high energy (~ 1nJ) laser pulses, with…

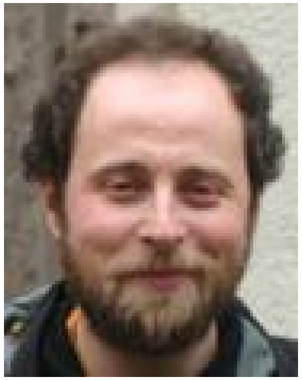
Welcome to Today's webinar!

OSA Laser Systems Technical Group

GAIN SWITCHED LASER DIODES FOR LASER RADARS & 3D LASER IMAGING WEBINAR

26 October 2017 • 12:00 EDT

OSA Laser Systems Technical Group



Dr. Eugene A. Avrutin
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Gain Switched Laser Diodes for Laser Radars and 3D Laser Imaging

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Outline

1. Brief summary of laser radar principle and requirements
2. The strategy of high-energy single pulse generation by gain switching
3. Asymmetric waveguide laser design and performance
4. Application example
5. Future developments and preliminary studies
6. Conclusions

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Emerging applications for laser radars/scanners

Collision Avoidance systems for UAVs

Autonomous Driving

Gesture Control

“Smart Home”

Robotics/Automation

Security

- miniature, inexpensive, low power, solid-state 1-D radars and 3-D system needed

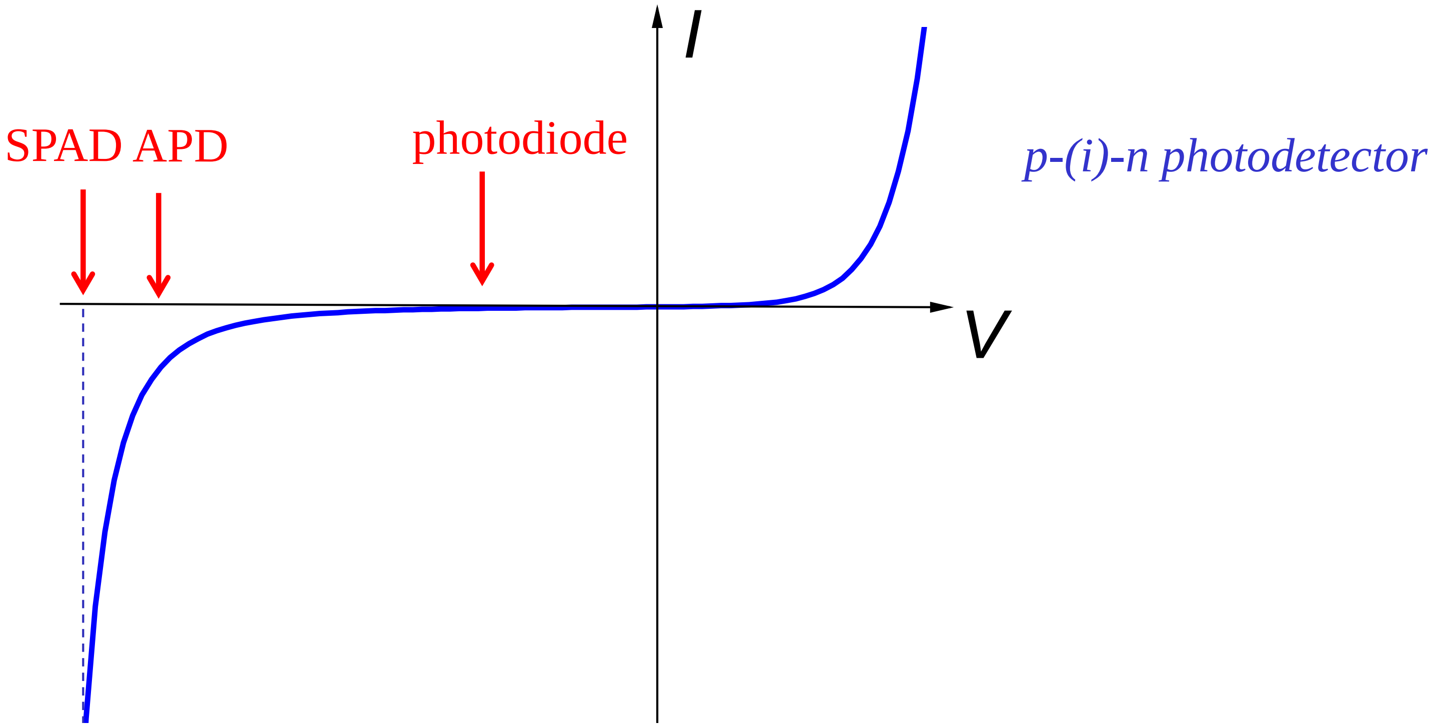
Time of flight laser radars

- Advantages over microwave radars :
  - Low cost potential (mass production friendly laser technology)
  - High resolution in the transverse direction (beam collimation by lenses
  - High resolution in distance (see later)

- Main types:
  - Continuously modulated laser (measurement of phase shift)
  - *Chaotic signal laser*
  - **Pulsed laser**

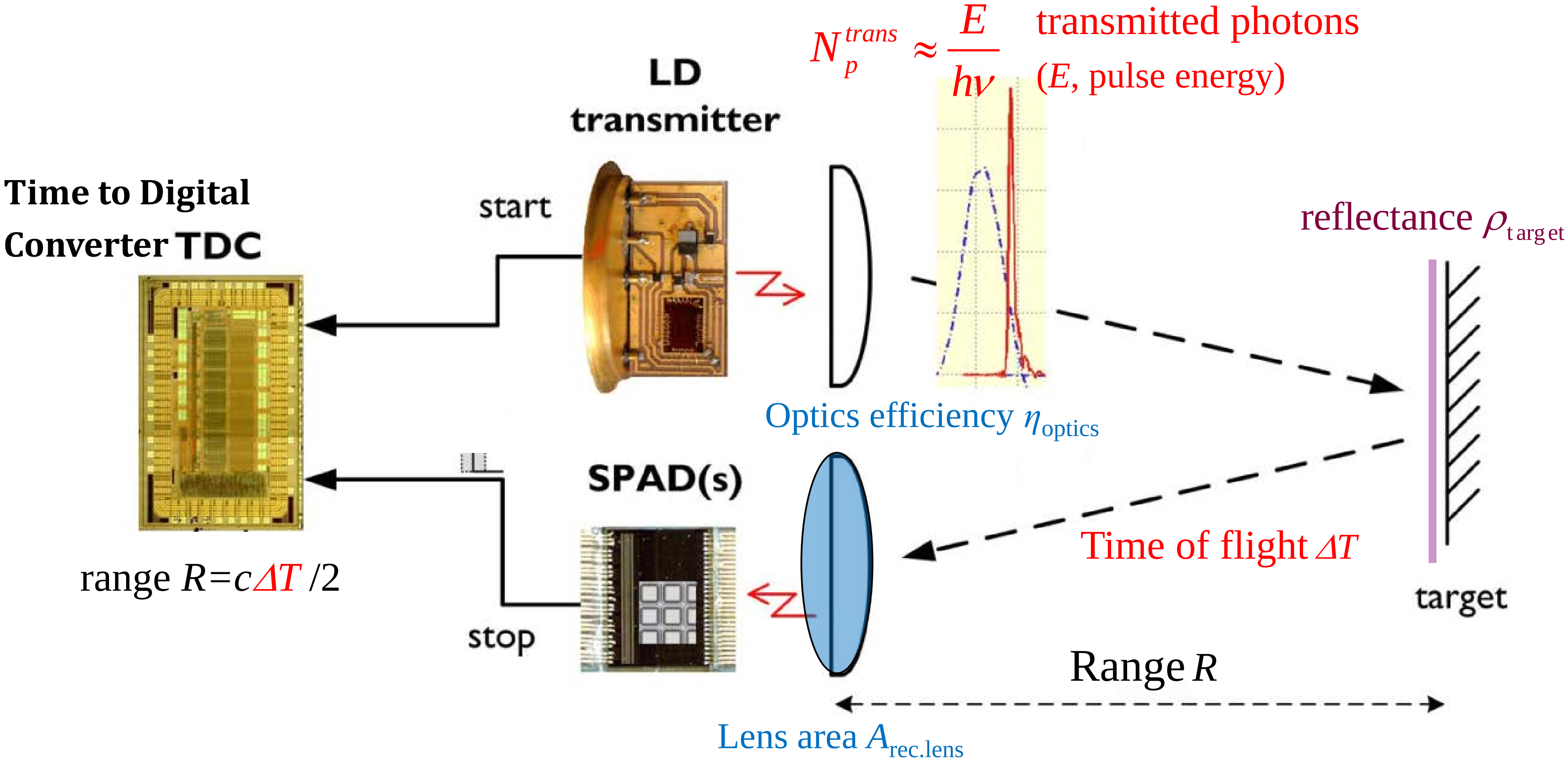
    - Good time resolution, even with single shot ⇒ high measurement speed
    - Relatively long unambiguous measurement range, limited by pulse repetition rate
    - Tolerant to multiple echoes in the case of splitting of optical beam

Detection in laser radars



- APD photodetectors for linear detection (signal envelope)
- SPAD (single photon avalanche detectors) for single photon detection
  - "Geiger counter" operating mode, single photon can trigger response
  - Timing jitter 50-100 ps
  - *Time gating* can be used to reduce triggering by background light

System operation schematic



$N_p^{trans} \approx \frac{E}{h\nu}$ transmitted photons (*E*, pulse energy)

Time to Digital Converter TDC

range $R = c\Delta T/2$

LD transmitter

reflectance ρ_{target}

Optics efficiency η_{optics}

SPAD(s)

Time of flight ΔT

Range R

Lens area $A_{rec.lens}$

$$N_p^{rec} \approx \frac{E}{h\nu}\rho_{target}\eta_{optics}\frac{A_{rec.lens}}{\pi R^2}$$

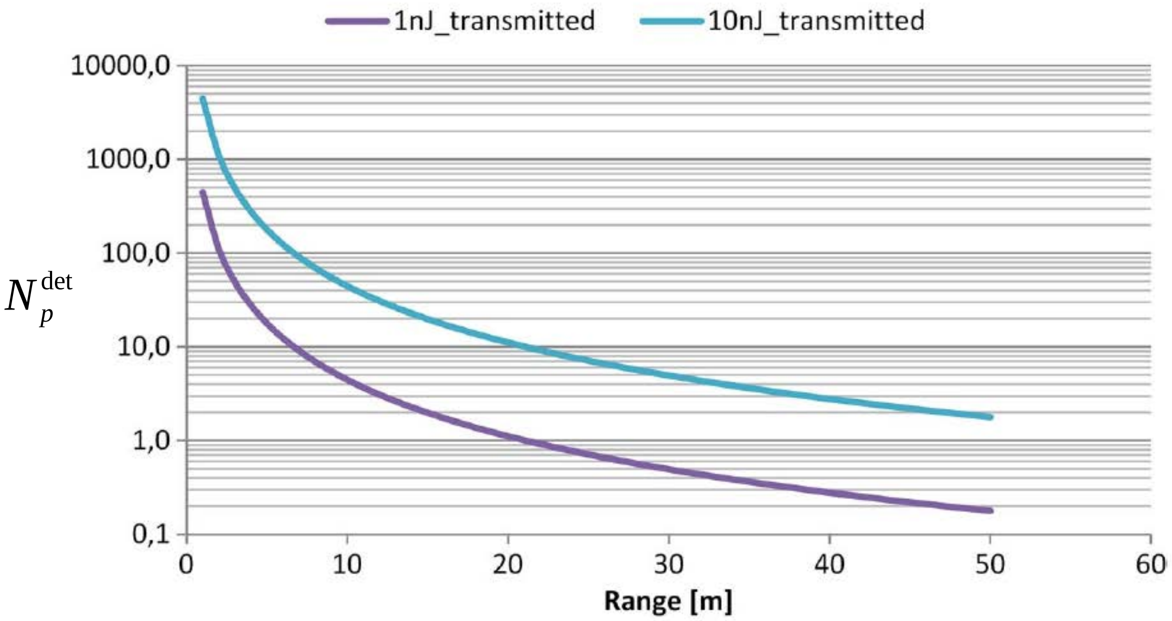
received photons **(radar equation)**

$$N_p^{det} \approx \eta_{det} N_p^{rec}$$

Detections (η_{det} photon detection efficiency, PDE, of the SPAD)

Launched & detected photon numbers and radar range

$$N_p^{rec} \approx \frac{E}{h\nu}\rho_{\mathrm{target}}\eta_{optics}\frac{A_{\mathrm{rec.lens}}}{\pi R^2} \qquad N_p^{\mathrm{det}} \approx \eta_{\mathrm{det}} N_p^{rec}$$



ρ_{target}=0.08

$A_{\mathrm{rec.lens}}$= 250 mm^2 (∅ = 18mm)

η_{optics}= 0.8

$h\nu$= 1.4 eV=2.3×10^{-19}J (λ=0.87 μm)

η_{det}=0.02 (note: λ↓⇒η_{det}↑)

$N_p^{\mathrm{det}} > 1$ multiphoton detection

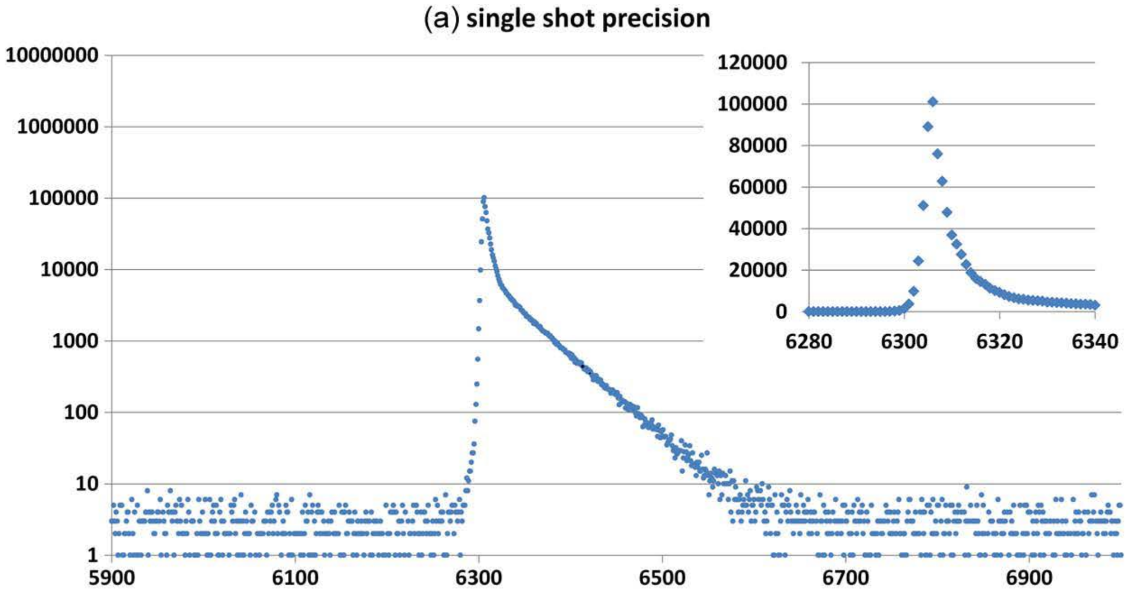
$N_p^{\mathrm{det}} <\sim 1$ single-photon detection

$N_p^{\mathrm{det}} < 1$ ⇒ effective detection frequency $F_{\mathrm{det}} = N_p^{\mathrm{det}} F_{trans} < F_{trans}$

So: $E > \sim 1$ nJ desirable for reliable detection at a few tens of metres

(commercial LIDARs with a range of 10 - 13 m in automotive applications are available, see e.g.
https://www.continental-automotive.com/getattachment/3918b2f6-8c47-421c-80b6-8773734931f3/SRL1-SRL1C-Datasheet-EN.pdf.aspx)

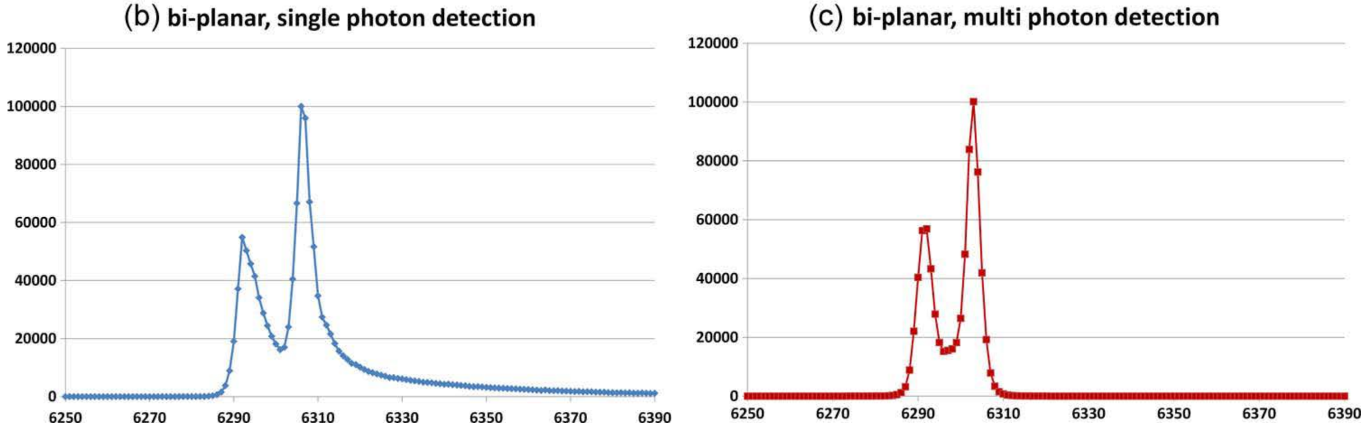
Time resolution: laser and SPAD effects



registration channel number: 1 channel = 24.5 ps

Time response a convolution of the laser pulse (here, ~ 100 ps) and SPAD response function

(here, ~50 ps)



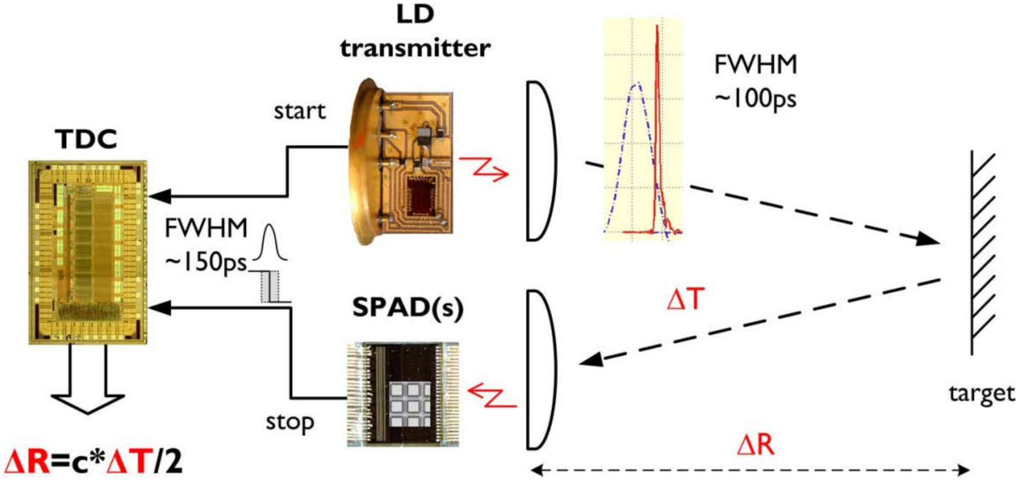
registration channel number: 1 channel = 24.5 ps

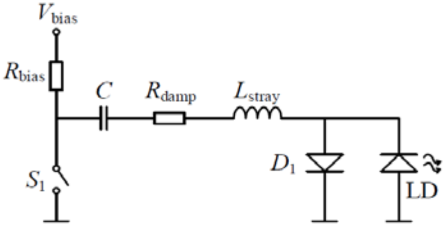
Multiple surfaces can be distinguished

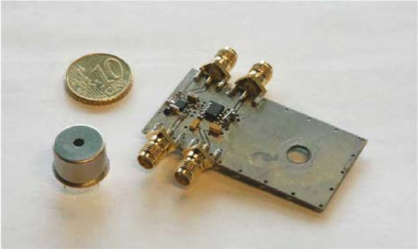
- a secondary pulse could lead to an artefact

Requirements for a laser pulse in pulsed TOD radar with a SPAD detector

1. > 1 nJ energy $\Rightarrow N_p^{rec}$







2. ~ 100 ps duration with no, or weak, trail of afterpulses ⇒ resolution)

3. Wavelength (so far, ~820-870 nm for Si SPAD ⇒ η_{det})

4. High brightness (good far field ⇒ η_{optics})

5. Modest pumping current pulse, ~10 A amplitude (Si electronics)

6. Mass production friendly, inexpensive source

Solution: gain switched laser diodes

- As all semiconductor lasers, are efficient, compact, and can be mass produced
- Power, pulse duration (and lack of afterpulsing structure) and beam properties are not guaranteed – but can be engineered

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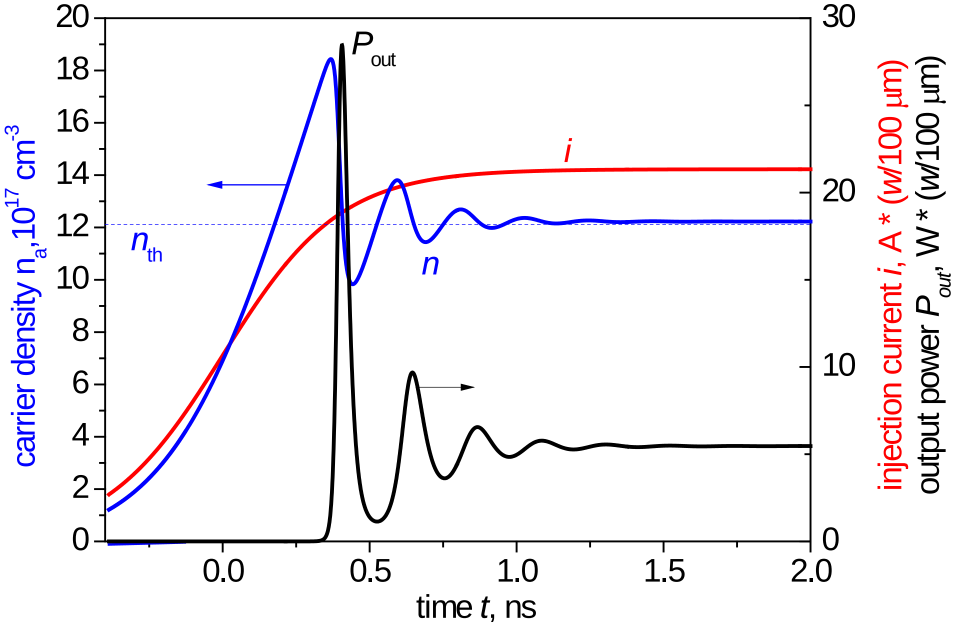
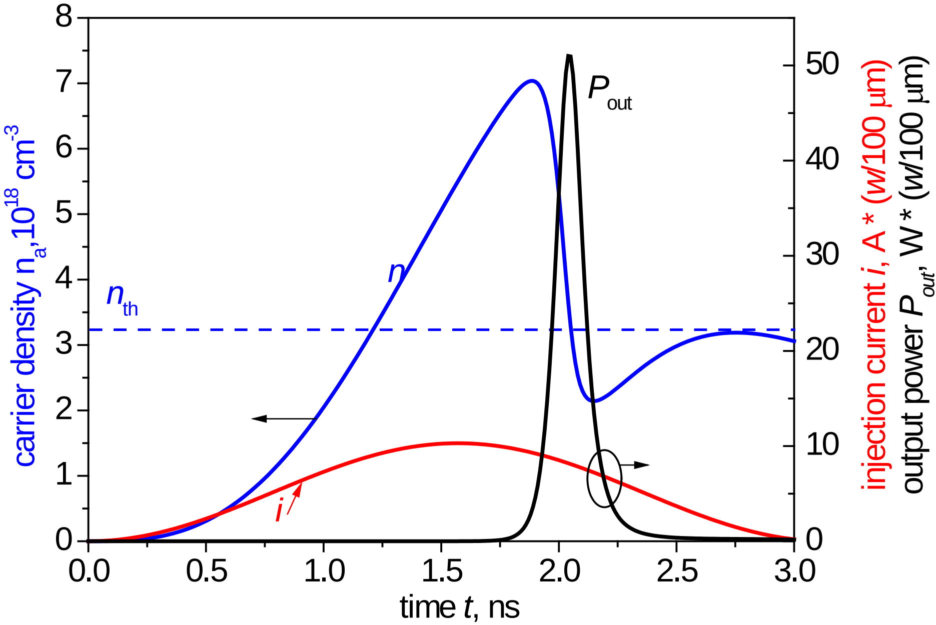
Gain switching: the definition used

Long pumping pulse: turn-on transient (relaxation oscillations, electron-photon resonance)



Short pumping pulse:

Gain switching (single optical pulse)



- Single, intense optical pulse (~10-100 ps) by a short (~ 1 ns or less) pumping pulse
- (the pumping pulse should be short and not too strong to prevent afterpulses)

Theoretical model: rate equations

Well-known and simple but almost surprisingly accurate. Predict qualitative trends very well; agree well with a more complex travelling wave model

pump recombination *Stimulated* recombination

$$\frac{dn}{dt} = \frac{i(t)}{eV} - \frac{n}{\tau_n(n)} - \Gamma_a v_g g(n, N_p)\frac{N_p}{V}$$

$$\frac{dN_p}{dt} = \left(\Gamma_a v_g g(n, N_p) - \frac{1}{\tau_p}\right) N_p + \frac{\beta_{sp} n V}{\tau_n(n)}$$

$$P_{out} = \hbar\omega \frac{N_p}{\tau_p^{out}}$$

gain loss spontaneous seeding

spontaneous recombination

$$\frac{1}{\tau_n(n)} \approx \frac{Bn^2}{1 + n / n_{sp}^{sat}} \quad \text{(GaAs/AlGaAs)}$$

$$\frac{1}{\tau_p} = \frac{1}{\tau_p^{in}} + \frac{1}{\tau_p^{out}}$$

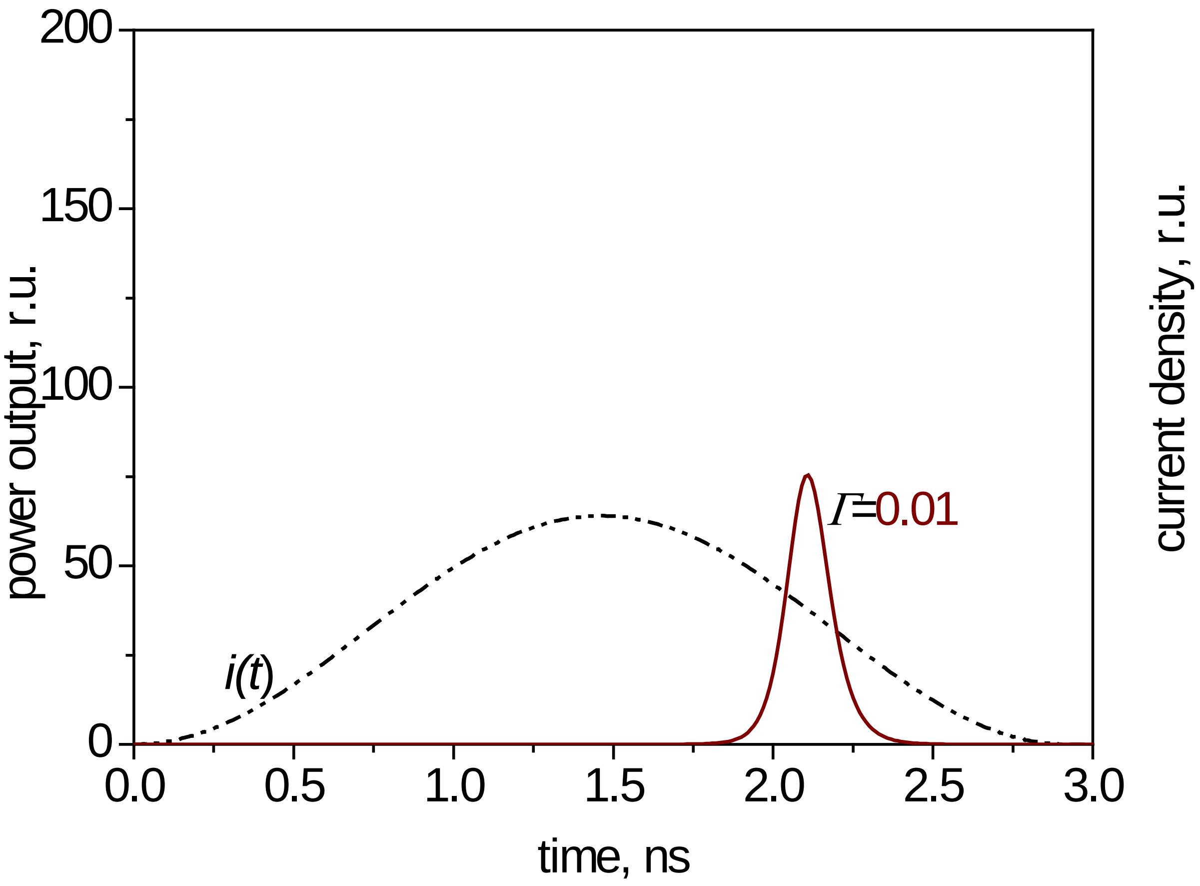
gain

$$g(n, N_p) = g_0 \ln\left(\frac{n - n_s}{n_{tr} - n_s}\right) \frac{1}{1 + \Gamma_a \varepsilon N_p / V} \quad \text{(QW)}$$

$$g(n, N_p) = \sigma\left(n - n_{tr}\right) / \left(1 + \Gamma_a \varepsilon N_p / V\right) \quad \text{(bulk)}$$

n is the active layer elctron and hole density, $\boldsymbol{N_p}$ is the number of photons in the laser; $\boldsymbol{d_a}$ is active layer thickness, $\boldsymbol{\Gamma_a}$ is the active layer optical confinement factor, ***L*** is the cavity length, ***w*** is the stripe width so $\boldsymbol{V=d_a wL}$ the cavity volume; τ_p is the photon lifetime due to outoupling and internal loss, $\mathbf{g_0}$ is the gain constant, ***B*** is bimolecular recombination coefficient, $\boldsymbol{\beta_{sp}}$ is the spontaneous emission factor, v_g is the group velocity of light, $\boldsymbol{\varepsilon}$ is the gain compression coefficient,

Gain switching: the effect of current over threshold



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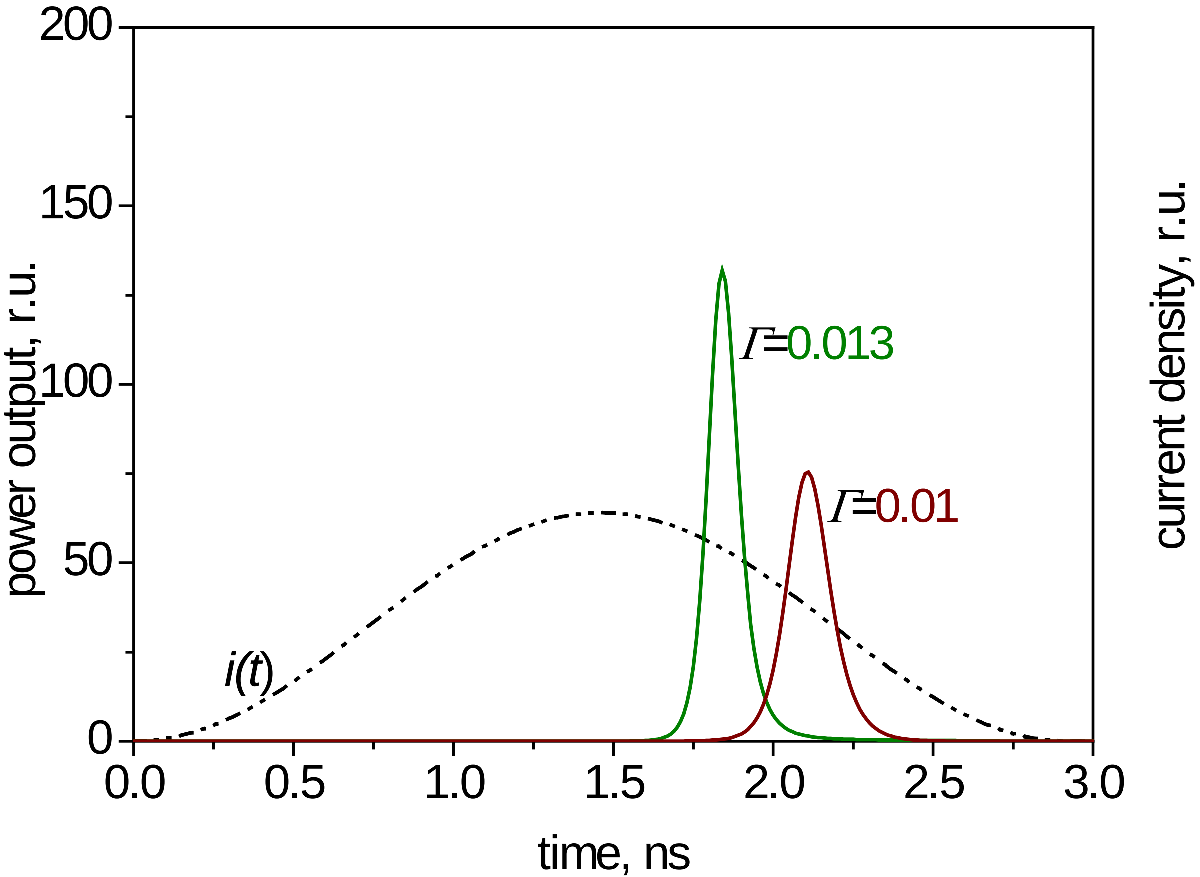
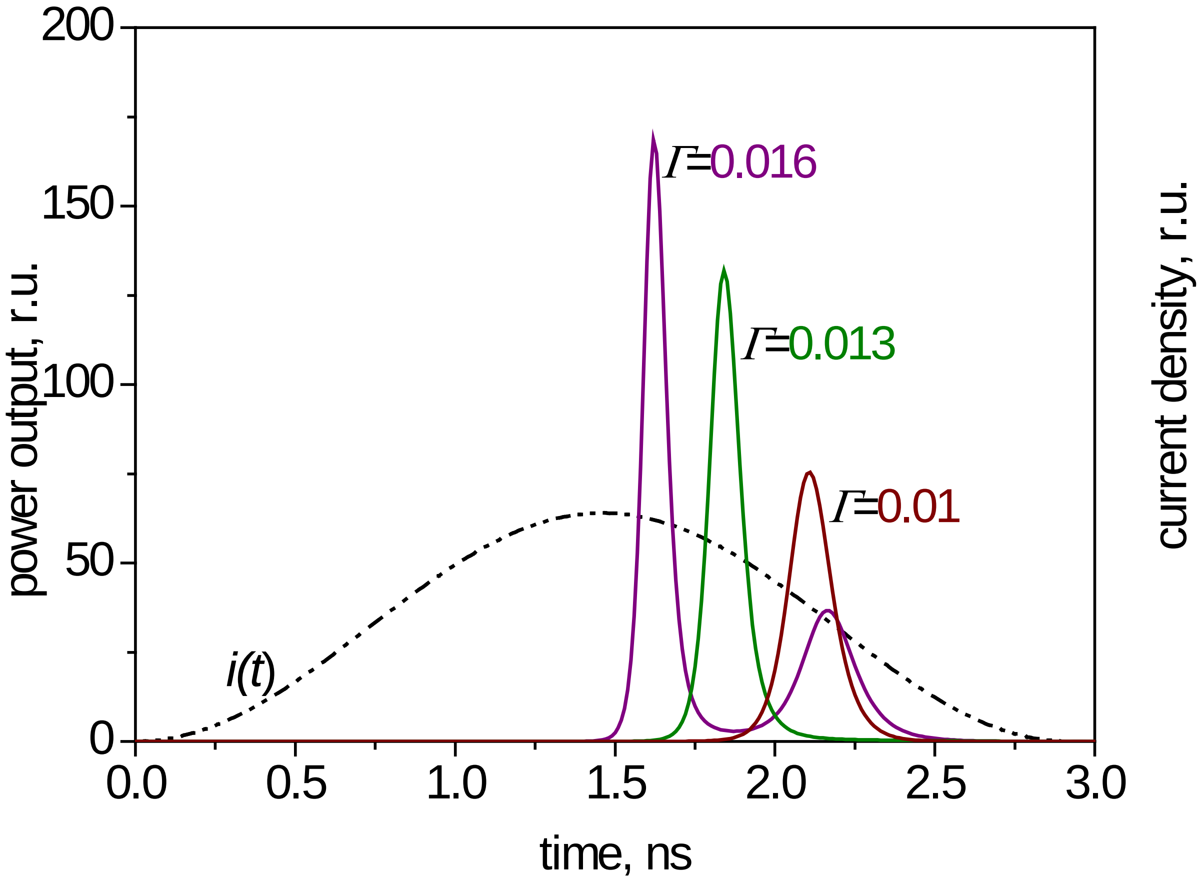


- As the current over threshold increases, the pulse peak power increases too

Gain switching: the effect of current over threshold



- As the current over threshold increases, the pulse peak power increases too
- but at high enough current over threshold, secondary pulses appear,

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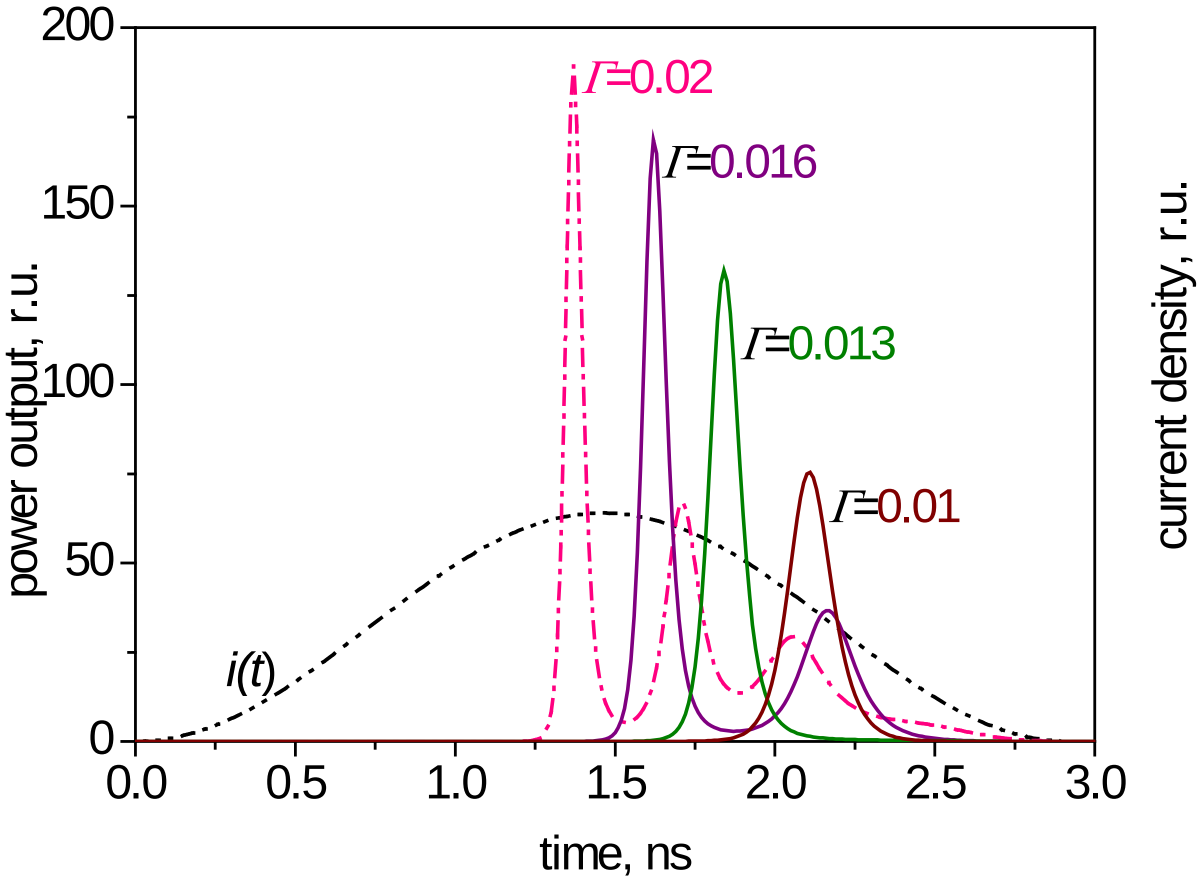

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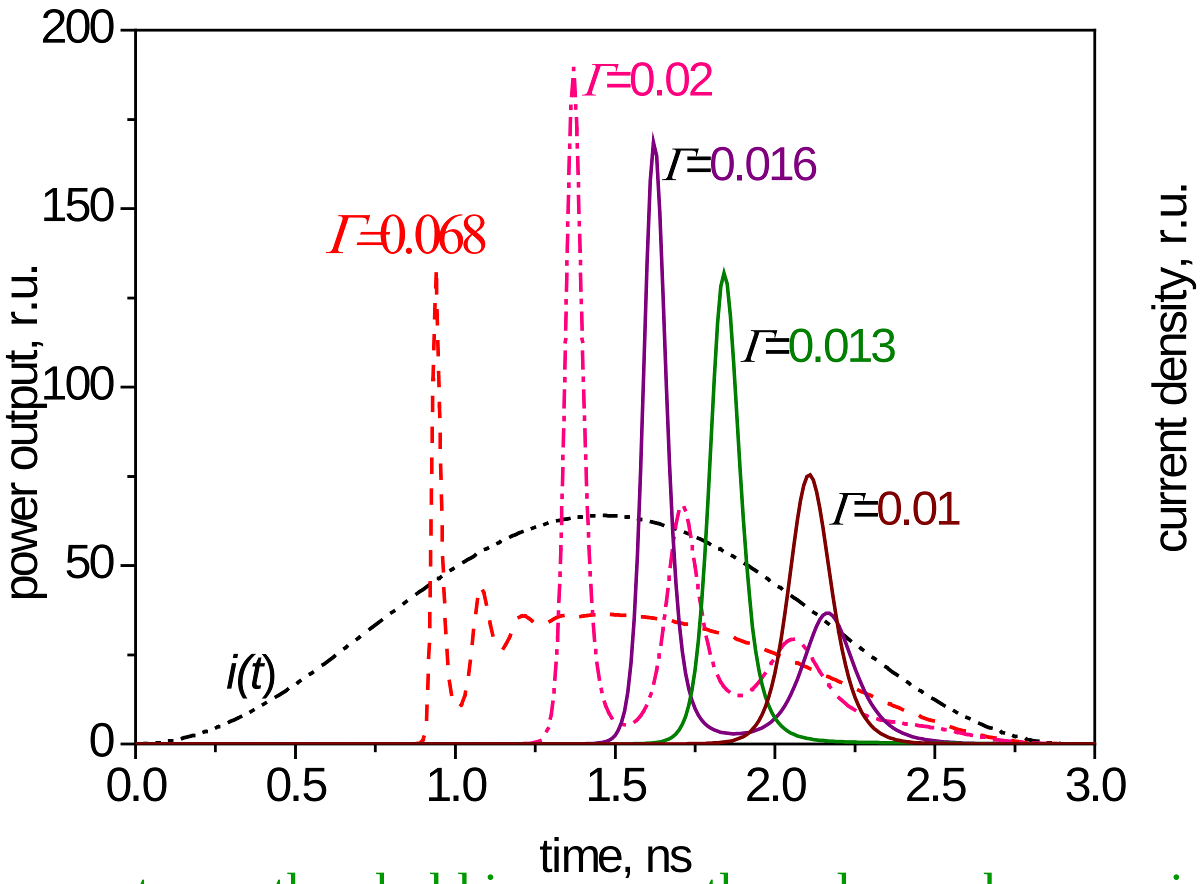


- As the current over threshold increases, the pulse peak power increases too
- but at high enough current over threshold, secondary pulses appear,
- Finally “normal” turn-on: relaxation oscillations then quasistationary

Rate equations: analytical solution (any material)

Fast stage (during pulse): neglect all terms except stimulated recombination

$$\frac{dn}{dt} \approx -\Gamma_a v_g g \frac{N_p}{V} \qquad \frac{dN_p}{dt} = \left(\Gamma_a v_g g - \frac{1}{\tau_p}\right) N_p$$

$$N_p\Big|_{t=0} = N_p\Big|_{t=\text{"}\infty\text{"}} = 0 \Rightarrow \int\limits_{fast\ stage} N_p dt = \tau_p \int\limits_{fast\ stage} \Gamma_a v_g g dt = \tau_p \Delta n$$

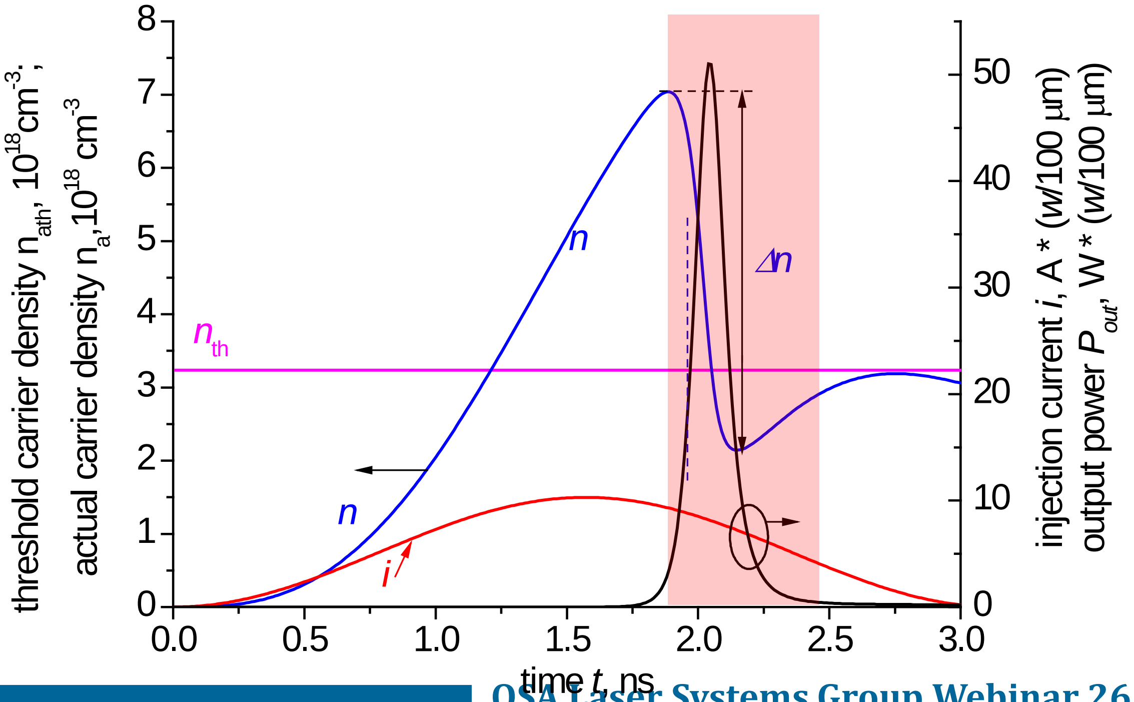
$$P_{out} = \hbar\omega \frac{N_p}{\tau_{p,out}} \Rightarrow \text{energy}=\int P_{out} dt = \hbar\omega \frac{\tau_p}{\tau_{p,out}} \boxed{V\Delta n}$$

The pulse energy is proportional to the variation of the number of carriers over the pulse

E.A.Avrutin *et al*, *J.Appl.Phys.* **110**, 123101 (2011) and ICTON 2014

derivation builds on earlier work in

- *E. Siegman, Lasers.* 1986,
- *K. Y. Lau, Appl. Phys. Lett.*, **52**, 257 (1988)



Rate equations: analytical solution contd.

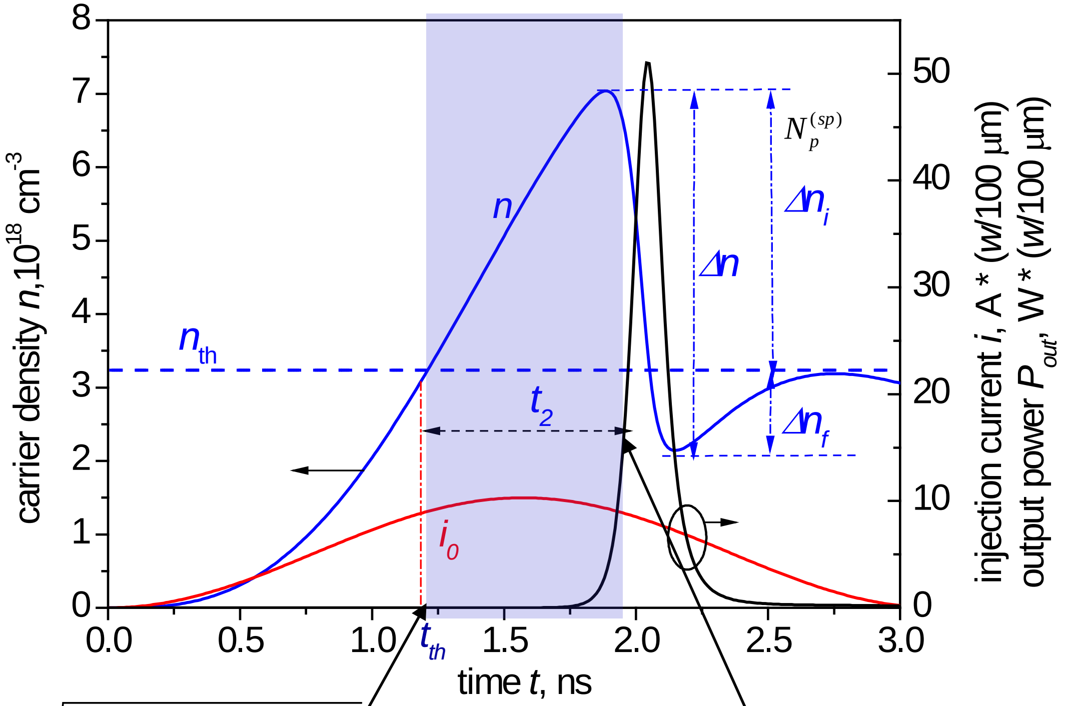
Slow stage (before pulse): *n* as accumulated while N_p grows from spontaneous seed

$$\frac{dn}{dt} \approx \frac{i(t)}{eV} - \frac{n}{\tau_n(n)} \approx \frac{i_0 - i_{th}}{eV} \Rightarrow n \approx n_{th} + \frac{i_0 - i_{th}}{eV}(t - t_{th})$$

$$\frac{dN_p}{dt} \approx \Gamma_a v_g \left(g - g(n_{th})\right) N_p \Rightarrow N_p \approx N_p^{(sp)} \exp\left(\Gamma_a v_g \left.\frac{\partial g}{\partial n}\right|_{n_{th}} \int_{t_{th}}^{t} \left(n(t') - n_{th}\right) dt' \right)$$

$$N_p\Big|_{t=t_{th}} = N_p^{(sp)}$$

$$N_p\Big|_{t=t_{th}+t_2} = N_{p1}$$



$$\Gamma_a \downarrow \;\Rightarrow\; t_2 \uparrow \;\Rightarrow\; \Delta n_i \uparrow$$

$$\Delta n_i \approx \sqrt{\frac{2\left(i(t_{th}) - i_{th}\right)}{\Gamma_a v_g eV} \left(\left.\frac{\partial g}{\partial n}\right|_{n_{th}} \right)^{-1} \ln \frac{N_{p1}}{N_{p,sp}}}$$

$$N_p^{(sp)} \approx \beta V \sqrt{\frac{2\pi n_{th}\left(n_{th} + n_s\right)}{\Gamma_a v_g g_0 \tau_n(n_{th})} \frac{i_{th}^{st}}{i(t_{th})}}$$

spontaneous
seed

$$N_{p1} \approx \frac{V\left(n_{th} + n_s\right)}{v_g g_0 \tau_n(n_{th})}$$

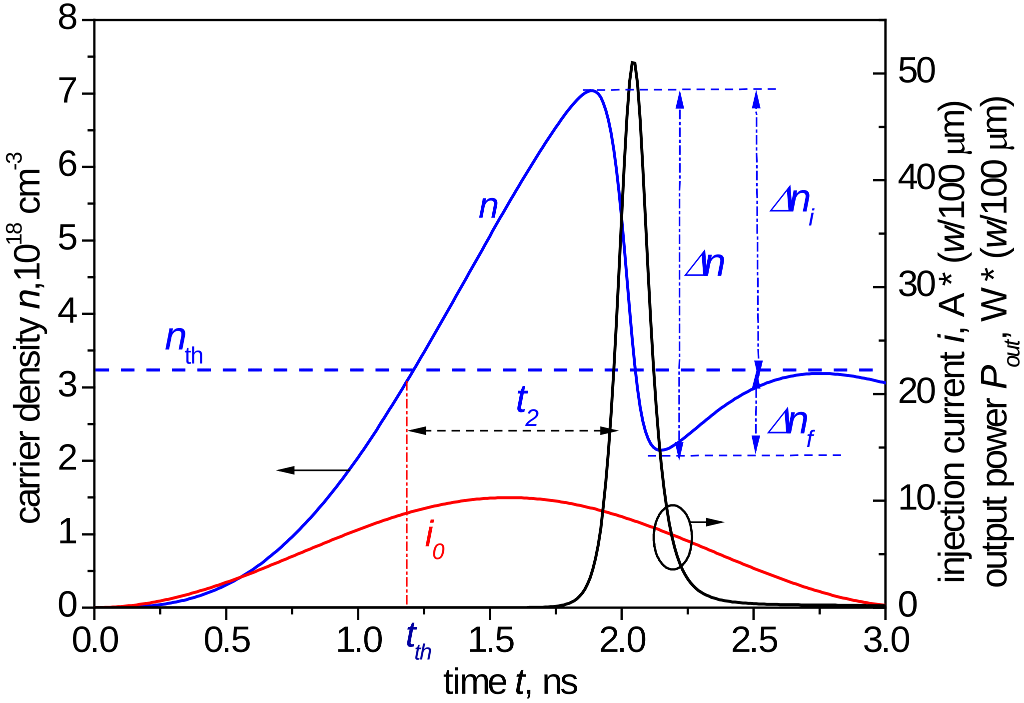
Stimulated recombination
~ spontaneous recombination

Why the confinement factor is important

1. $\Gamma_a \downarrow \Rightarrow \Delta n_i \uparrow$

$$\Delta n_i \uparrow \Rightarrow \Delta n_f \approx \Delta n_i \left(1+\frac{2}{3}\frac{\Delta n_i}{n_0}\right)^{-1} \uparrow$$

$$n_0 = g_{th}\left(\left.\frac{\partial g}{\partial n}\right|_{n_{th}}\right)^{-1}$$



$$\Rightarrow \text{energy } \; E=\eta_{out}\hbar\omega\left(\Delta n_i+\Delta n_f\right)V \approx \text{const}\times\sqrt{V/\Gamma_a} \quad \uparrow$$

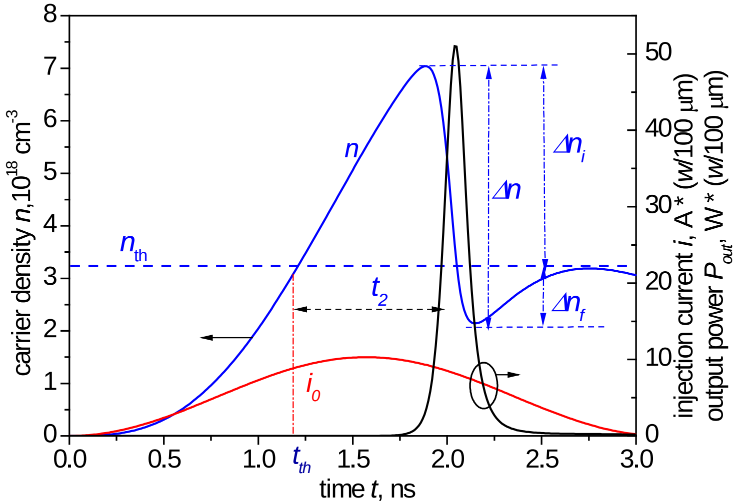
Why the confinement factor is important: contd.

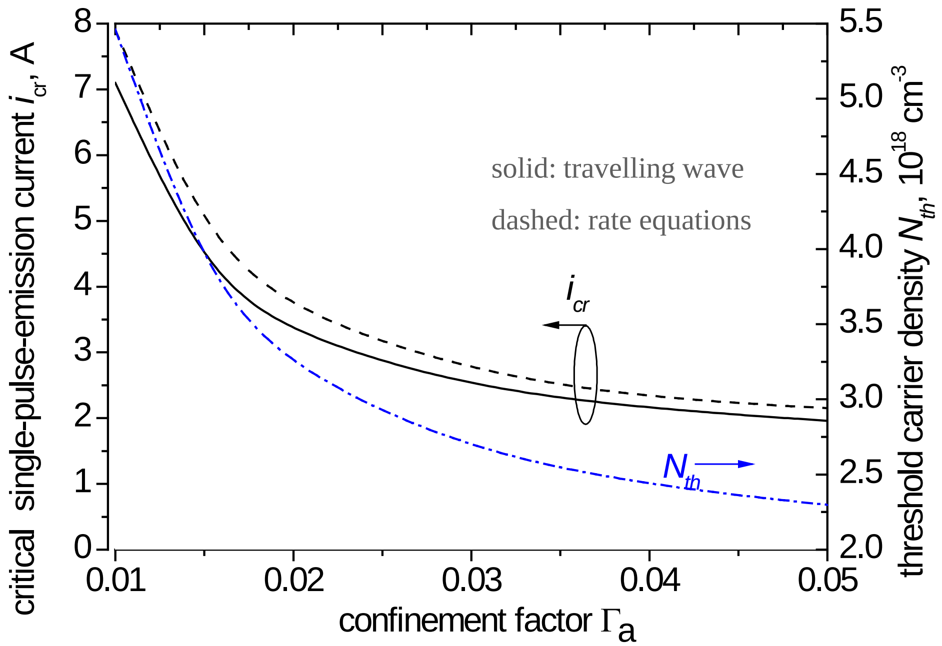
2. $\Delta n_i \uparrow \Rightarrow \Delta n_f \uparrow$

.

$$\Delta n_f \approx \Delta n_i \left(1 + \frac{2}{3}\frac{\Delta n_i}{n_0}\right)^{-1}$$

$\Rightarrow$ single pulse to higher currents





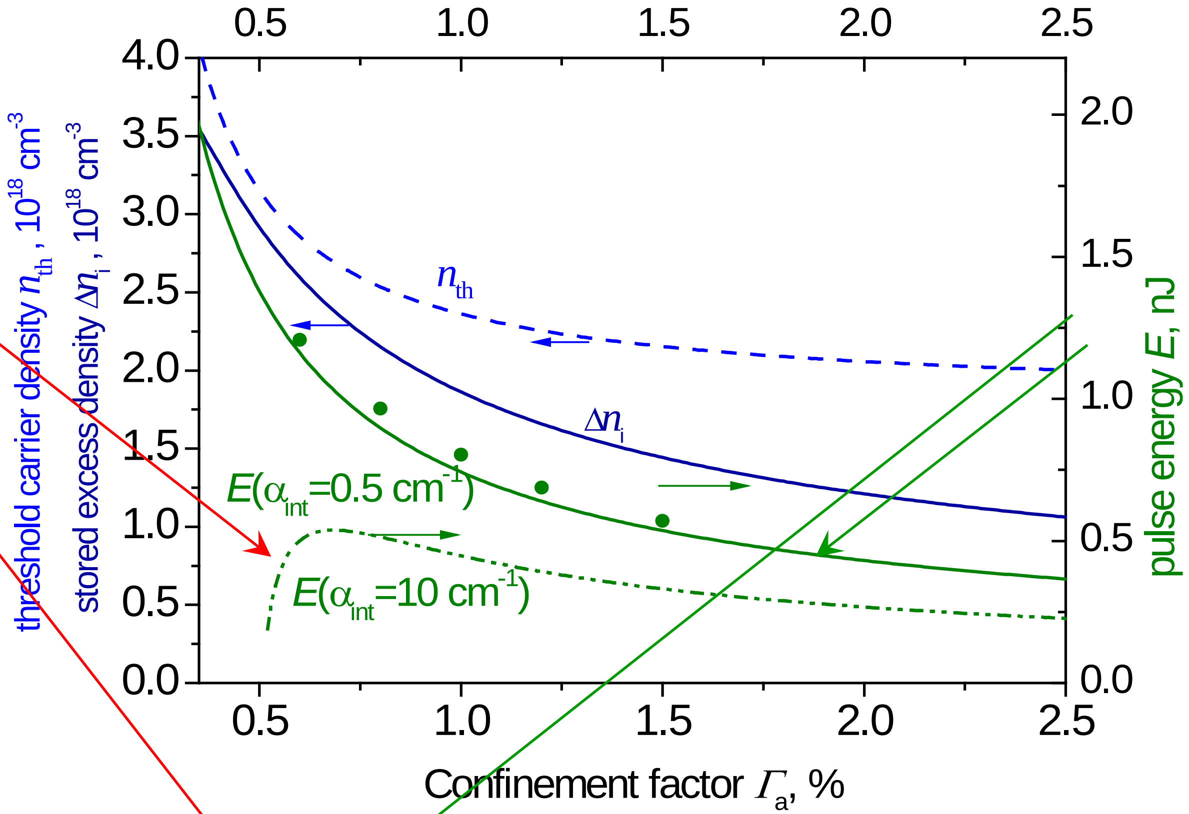
B.S.Ryvkin, E.A.Avrutin, J. Kostamovara,
IEEE/OSA JLT,
27, 2125-2131**,** 2009

Bulk material

w= 100 μm

Stored carrier density and energy dependence on confinement factor

Decreased current over threshold



Increased Carrier storage

$$\Delta n_i \approx \sqrt{\frac{2(i(t_{th})-i_{th})}{\Gamma_a v_g eV}\left(\left.\frac{\partial g}{\partial n}\right|_{n_{th}}\right)^{-1}\ln\frac{N_{p1}}{N_{p,sp}}}$$

There is an optimum value of Γ_a , **smaller than typical in diode lasers**

Laser designs with small Γ_a (large equivalent spot size d/Γ_a)

Investigated by a number of teams, for both CW operation and/or gain-switching(*)

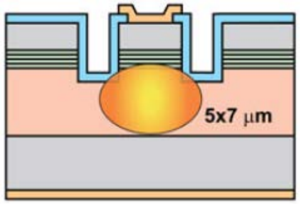
- Slab-Coupled Optical Waveguide (SCOW)

e.g. P. W. Juodawlkis *et al.*,

IEEE J. Select. Top. Quant. Electron., 17, 1698, 2011

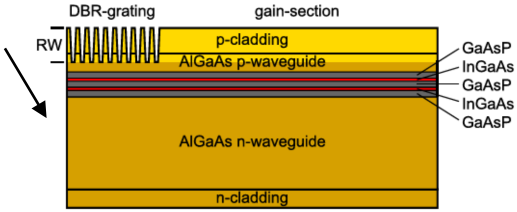
and references therein

Symmetric waveguide, single transverse mode for narrow enough stripe width

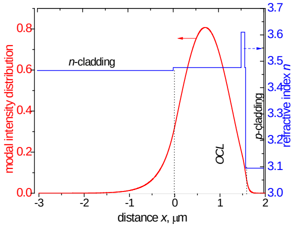


- Asymmetric active layer position*

e.g. A. Kaltenbach *et al.*, *Proc. SPIE*, **10088**, 108808, 2017*.

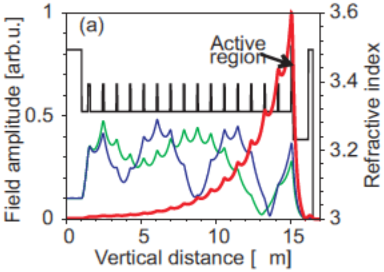


- Asymmetric waveguide structure *and* active layer position (our approach)



  - Photonic Crystal waveguide Structures*

R. Rosales *et al.*, *IEEE Photon. Technol. Lett.* 17, 1698, 2016*



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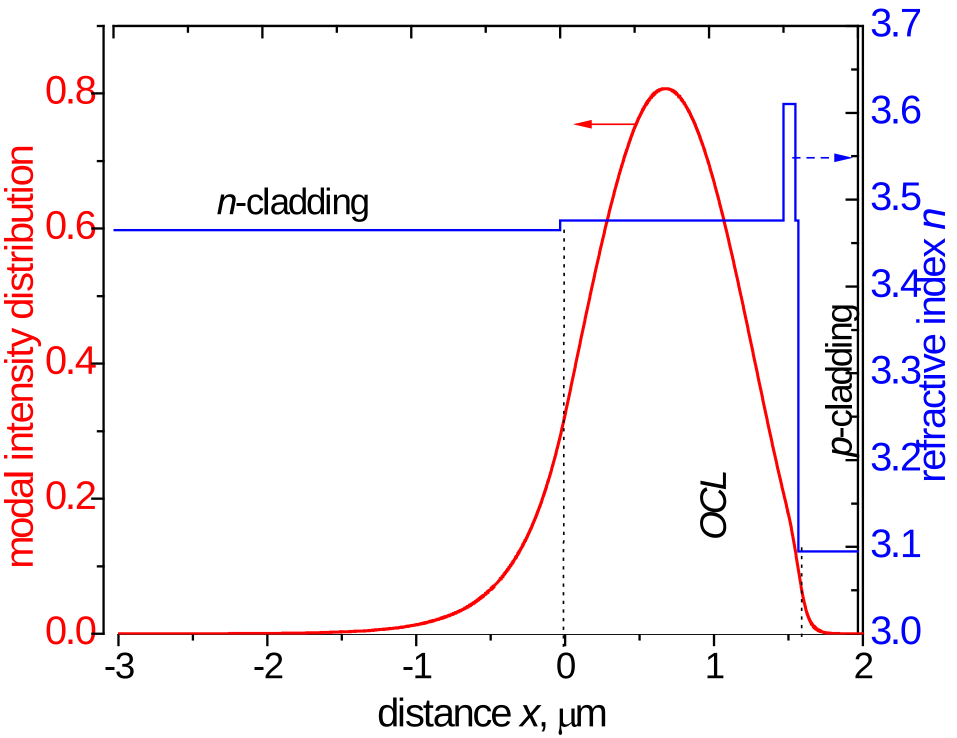
Asymmetric waveguide gain switched laser design



Broad waveguide ($\Gamma_{OCL} > \Gamma_{\text{n-clad}}$)
Double asymmetry (active layer position and refractive index)

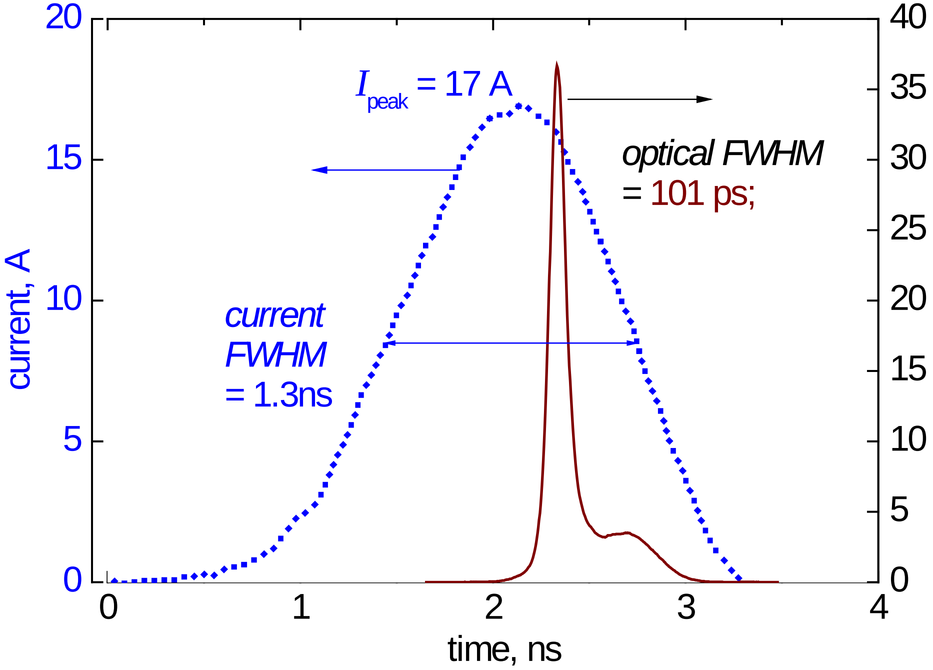
Single transverse mode for any stripe width, low loss

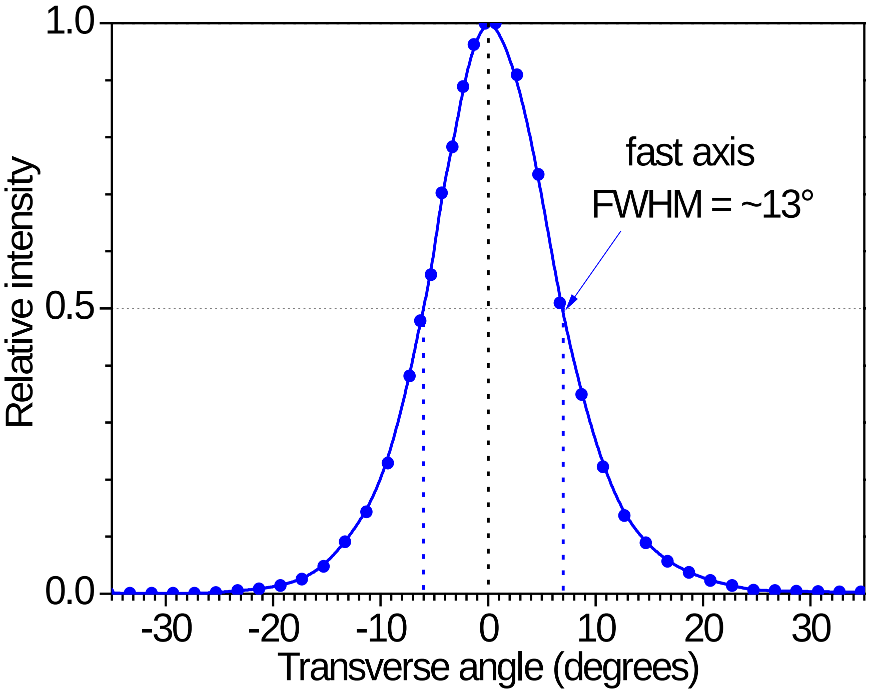
Bulk or MQW active layer, $d/\Gamma_a \sim$ 3-8μm

Theoretically proposed in
B.S.Ryvkin, E.A.Avrutin, J. Kostamovara, *JLT*, **27**, 2125 (2009)
Realised experimentally for gain switching
L. Hallman *et al*., *Electron. Lett*. **46**, 65(2011)
B. Lanz *et al*., *Opt. Express* **21**, 29780(2013)
J.Huikari *et al JSTQE*., **22**, 1501206 (2015)
J.Huikari *et al Opt.Rev.*, **23**, 522(2016)
and for CW lasing, see e.g.
P. Crump *et al*, *IEEE JSTQE* **19**, 1501211, 2013

Broad stripe asymmetric waveguide gain switched laser with a bulk active layer: experiment

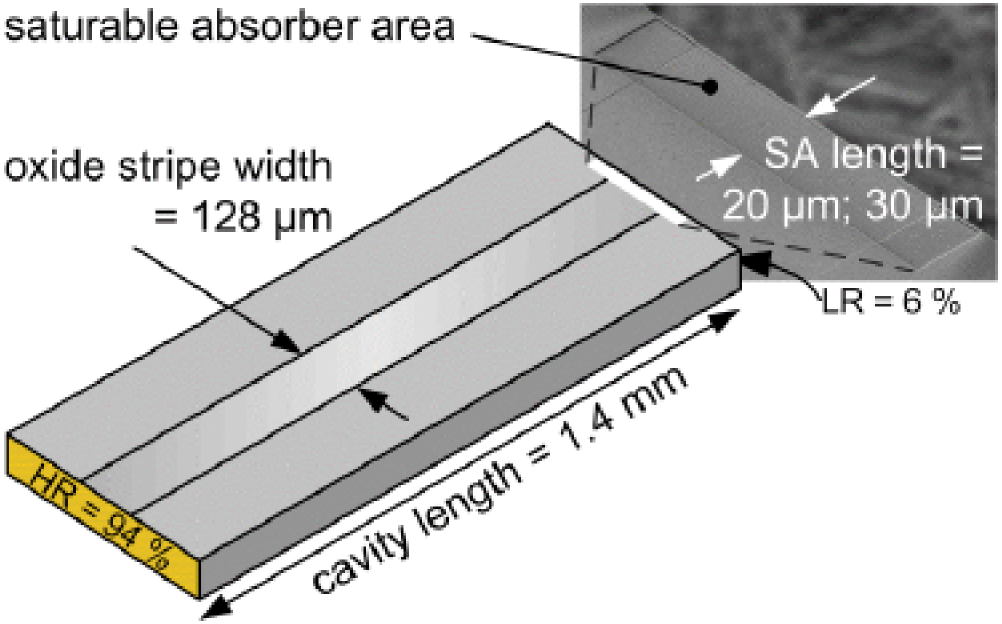
d=80 nm, Γ_a~0.03





- Very good transverse (fast axis) far field
- Optical pulses about 50-100 ps long
- Some trailing structure at higher currents

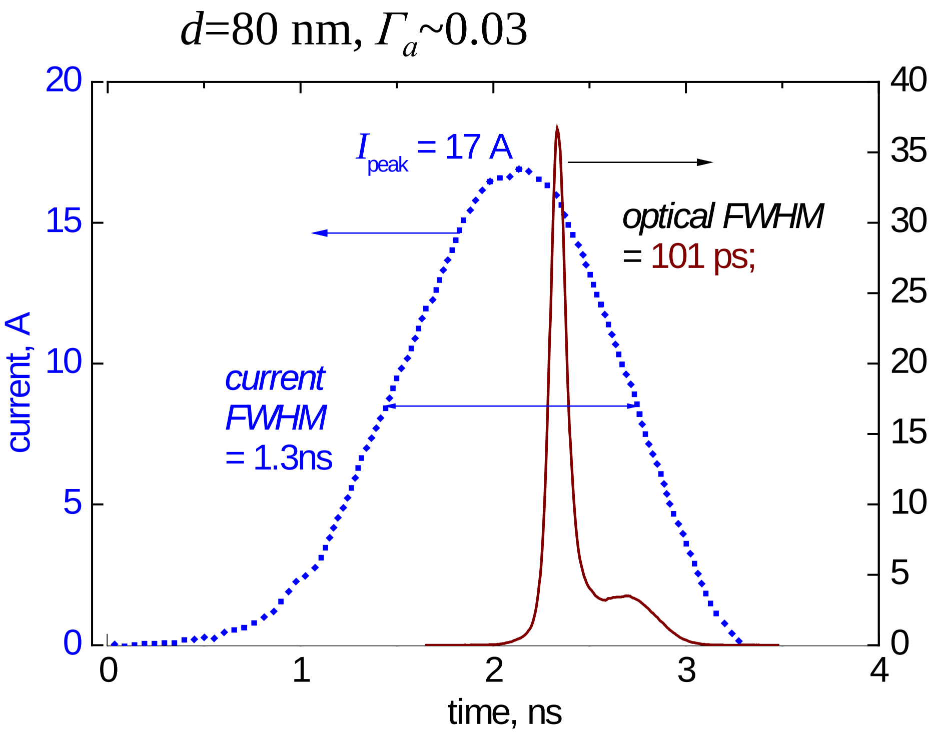
Lasers with a saturable absorber: hybrid Gain-switching/Q-switching regime

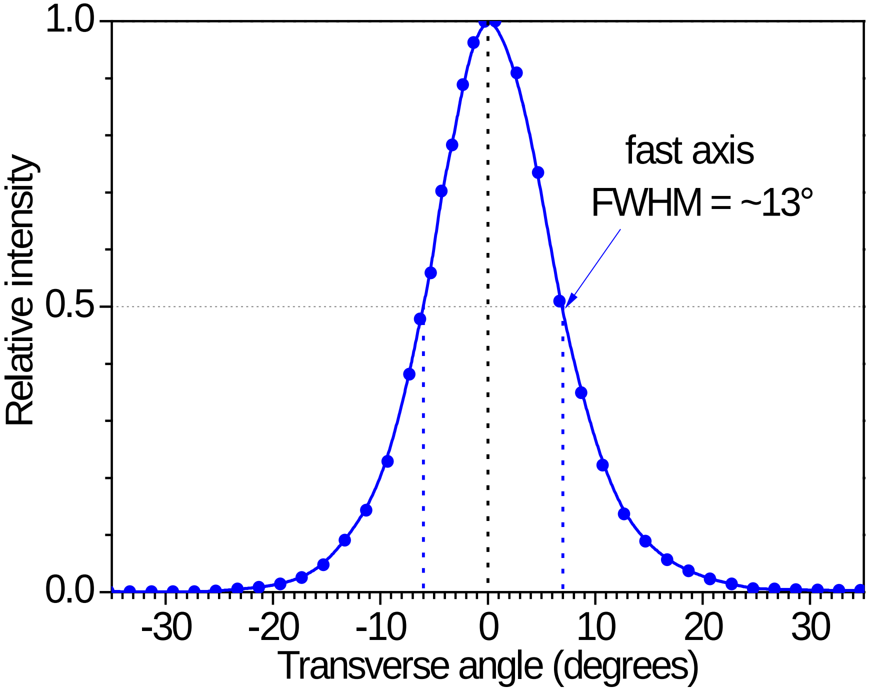


- Short uncontacted saturable absorber (at AR-coated side).
- No repetitive Q-switching observed
- But significant effect on gain-switching : combined regime

B. Lanz *et al.*, *Optics Express*, **21**, (24) 29780-91, 2013

Broad stripe asymmetric waveguide gain switched laser with a bulk active layer: experiment





- Very good transverse (fast axis) far field
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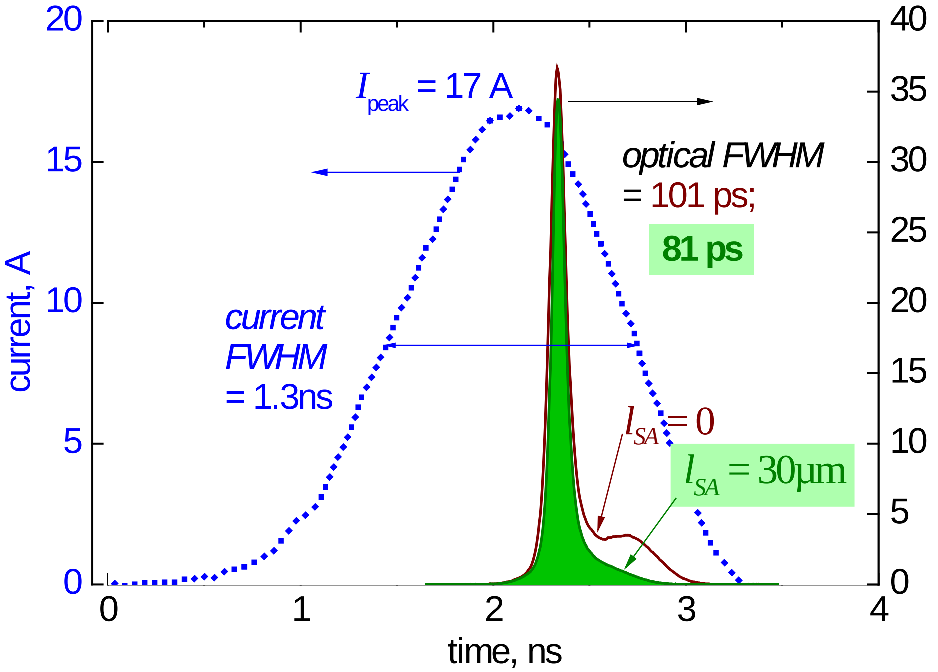
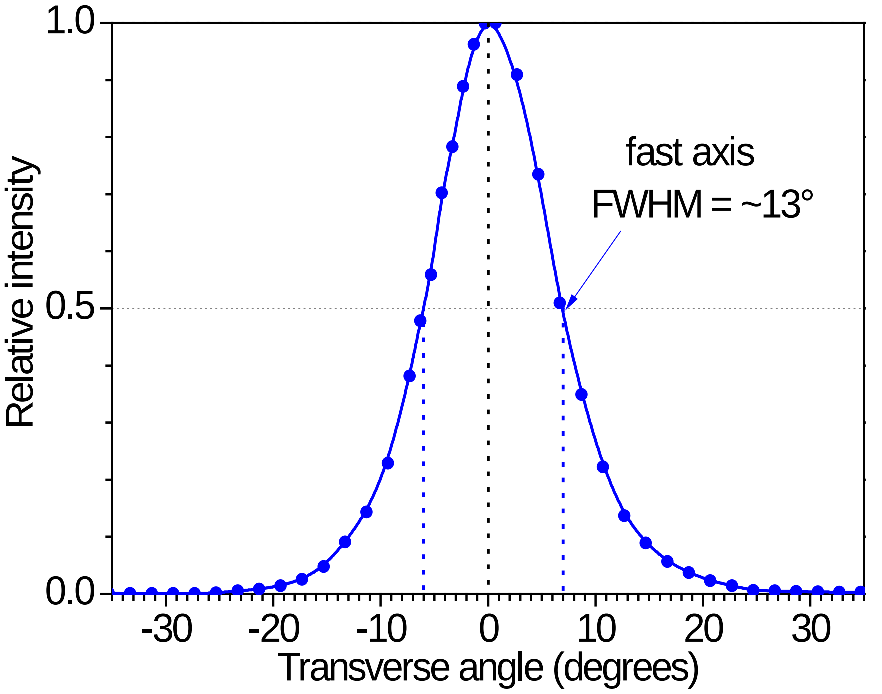
B. Lanz *et al.*, *Optics Express*, **21**, (24) 29780-91, 2013

Broad stripe asymmetric waveguide gain switched laser with a bulk active layer: experiment

d=80 nm, Γ_a~0.03



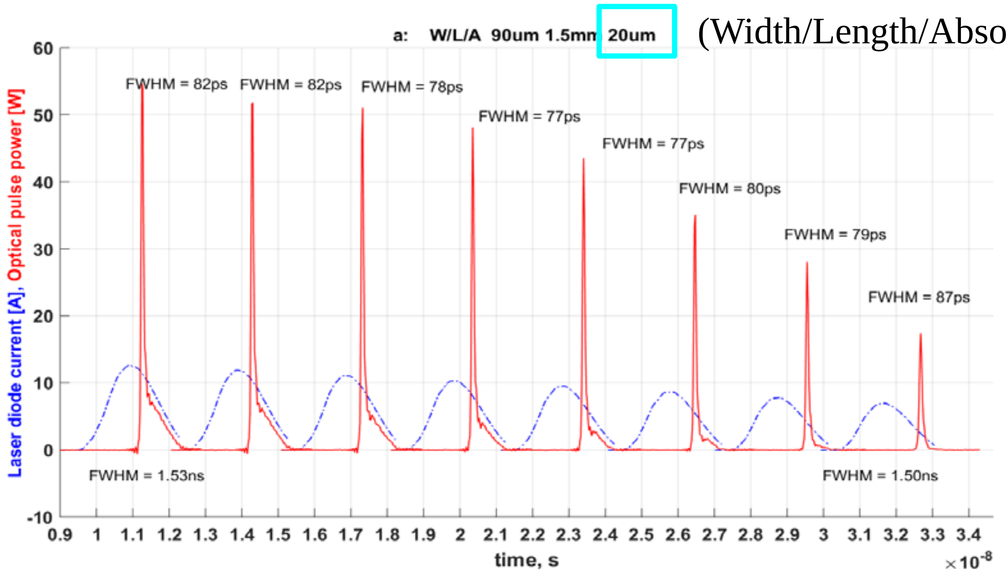


- Very good transverse (fast axis) far field
- Optical pulses about 50-100 ps long
- Some trailing structure at higher currents –

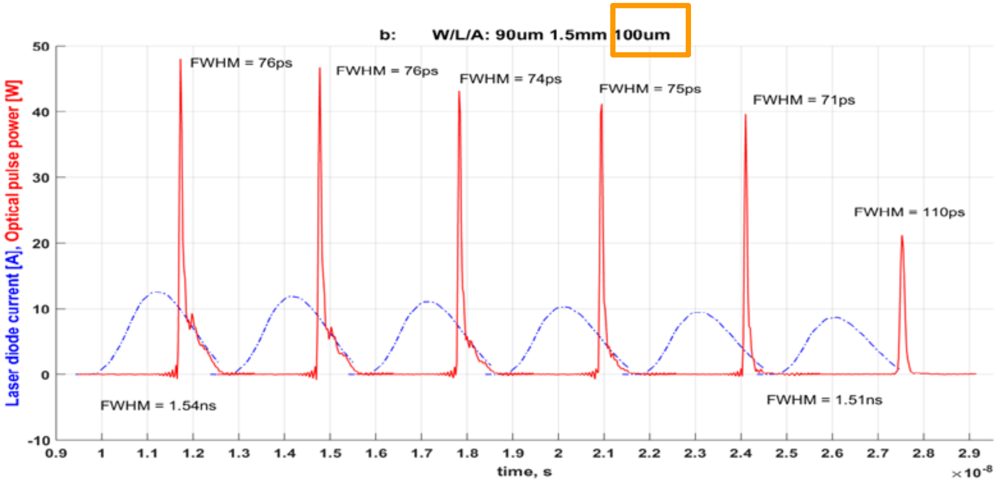
can be removed by an integrated absorber

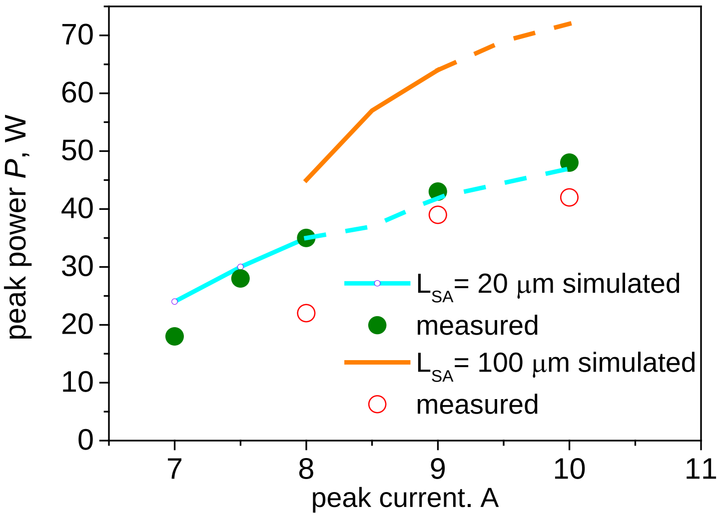
B. Lanz *et al.*, *Optics Express*, **21**, (24) 29780-91, 2013

Bulk lasers with a saturable absorber: absorber length effect



(Width/Length/Absorber length)

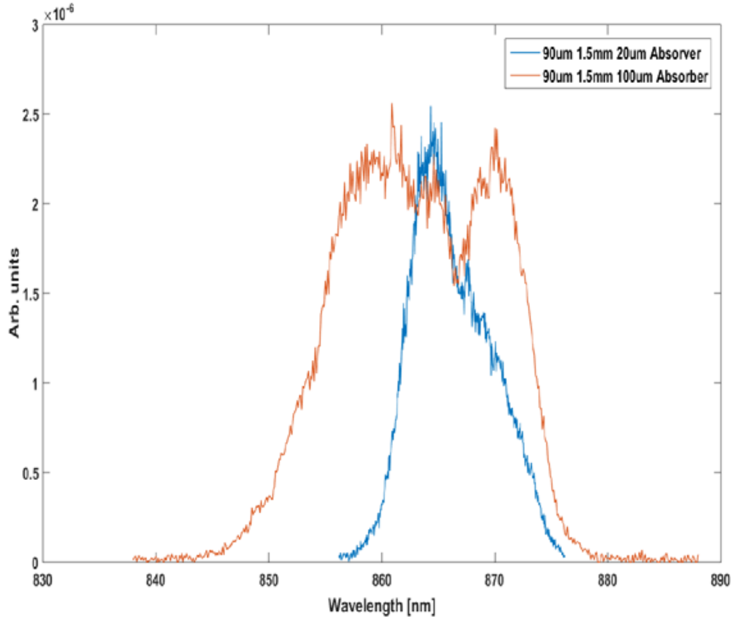




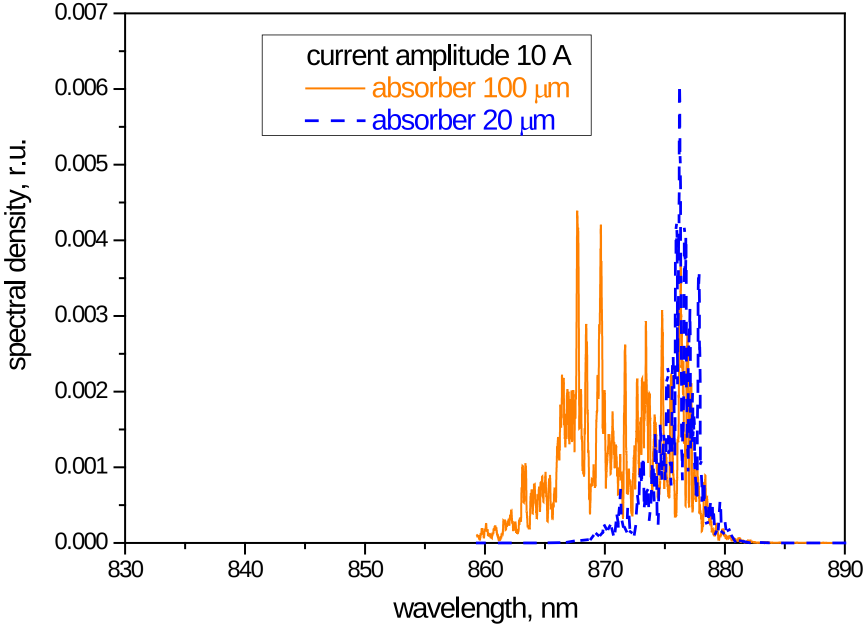
- Experimentally, lasers with longer absorbers show performance not as good as shorter ones (not reproduced by simulations - some non-saturable absorption introduced?).

Bulk lasers with a saturable absorber: absorber length effect on spectrum

measurement



Travelling wave simulation



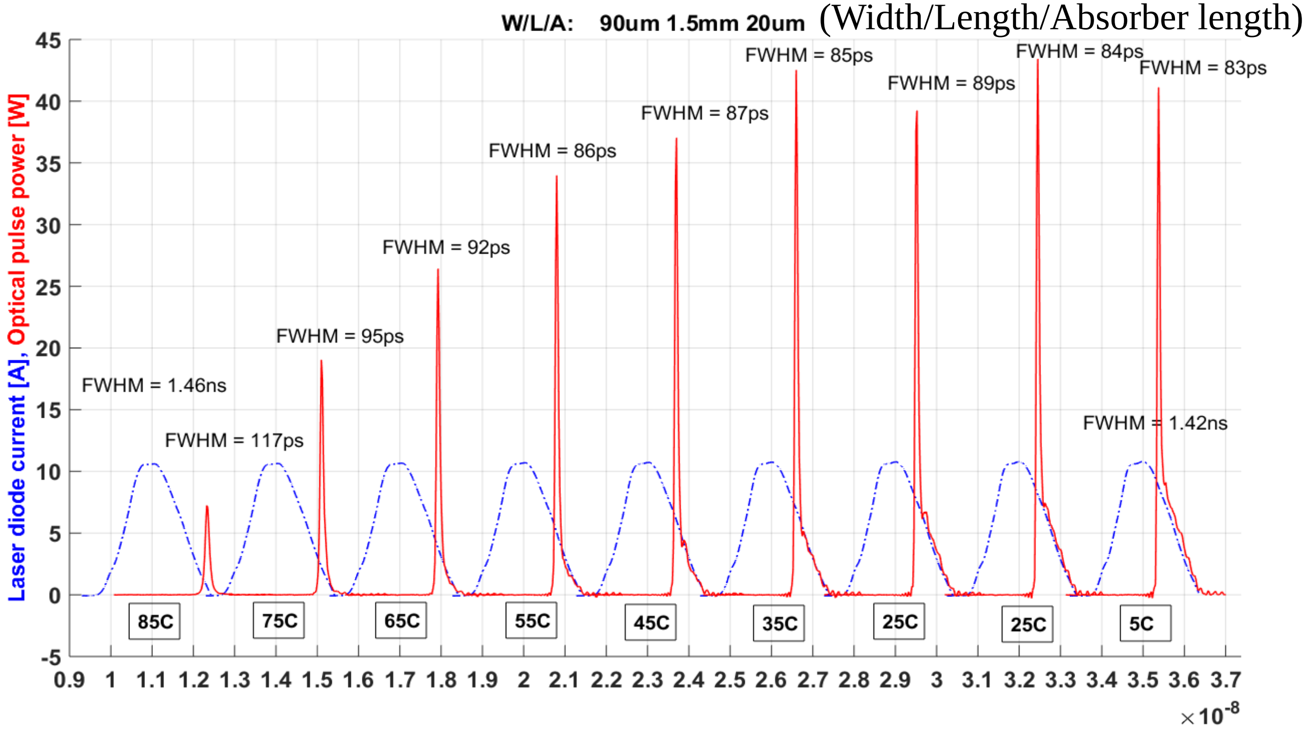
- Longer saturable absorber gives a considerably broader spectrum in a Fabry-Perot laser – explainable on the basis of gain peak shift and broadening.
- Undesirable in LIDAR systems
- So from this viewpoint too, a short absorber appears optimal

B.S. Ryvkin, E.A.Avrutin, J.E.K. Kostamovaara, J.T.Kostamovaara,

Semicond.Sci.Technol, **32**, 025015, 2017

Temperature effect on bulk laser performance

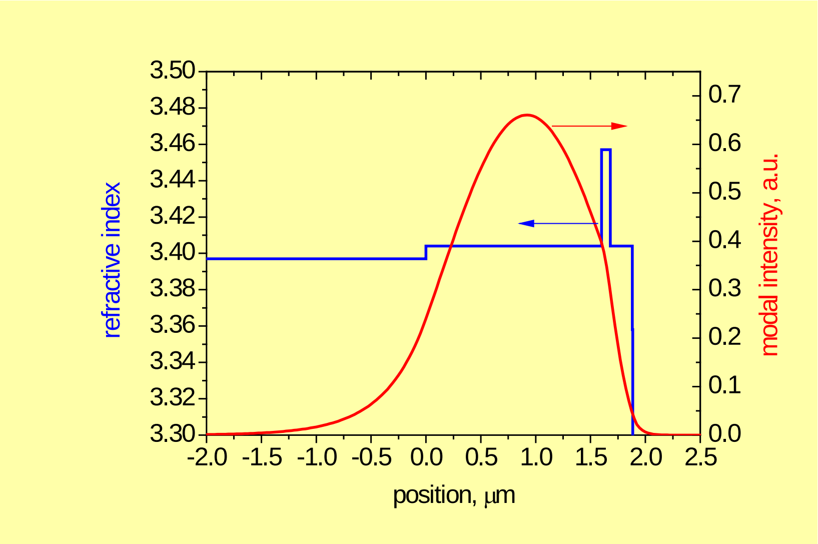
(with or without absorber)

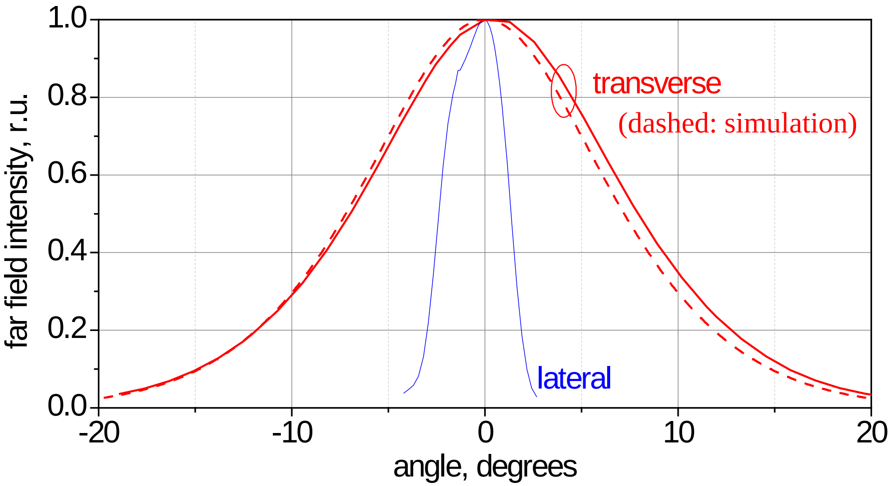


(Width/Length/Absorber length)

- Strong heating decreases pulse amplitude – but by increasing threshold, removes afterpulsing structure.

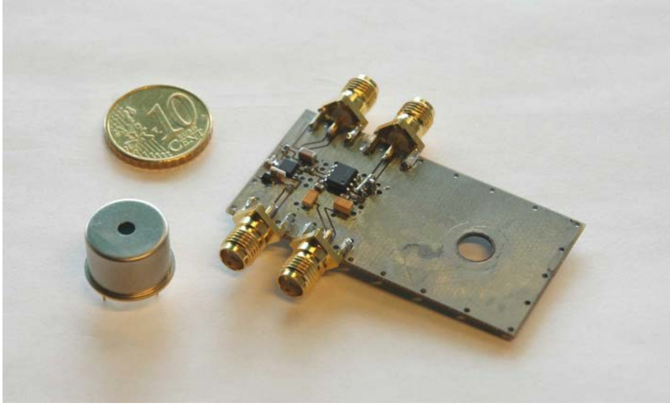
Broad asymmetric waveguide MQW gain switched laser: Experimental performance (1)





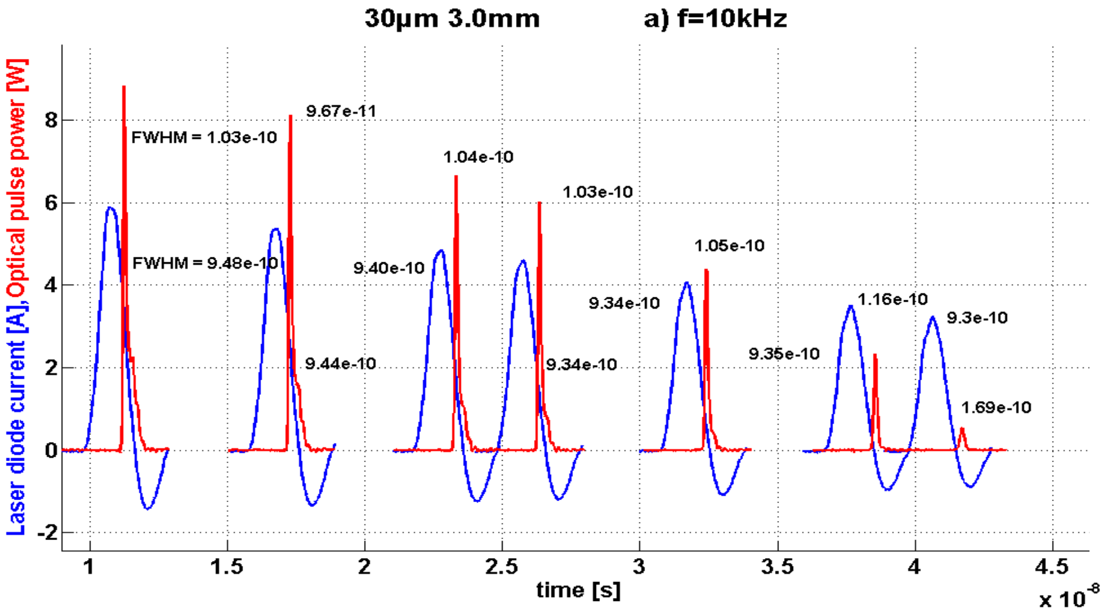
MQW active layer, d/Γ_a~ 4μm, 5 GaAs/Al$_{0.3}$Ga$_{0.7}$As QWs 40 Å each:
λ=808 nm, increasing sensitivity of Si SPADs
for improved PDE η_{det} (from ~0.02 to ~0.04)

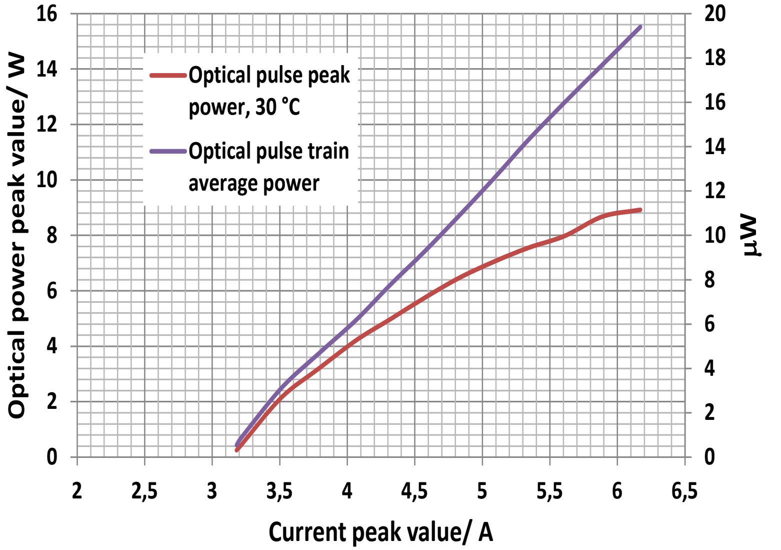
Narrow far field, as designed



J. Huikari *et al*, *IEEE J Select.Top. Quantum Electron*, **21** (6), 1501206, 2015

Broad asymmetric waveguide MQW gain switched laser: Experimental performance (2)



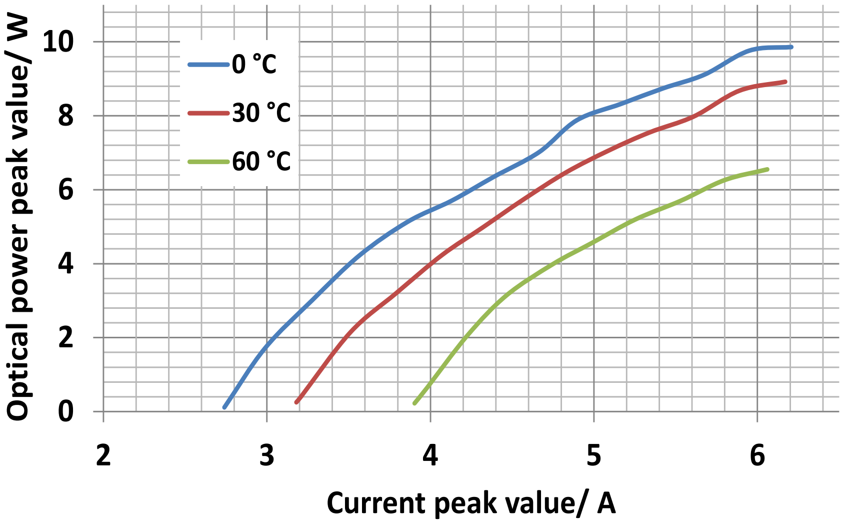


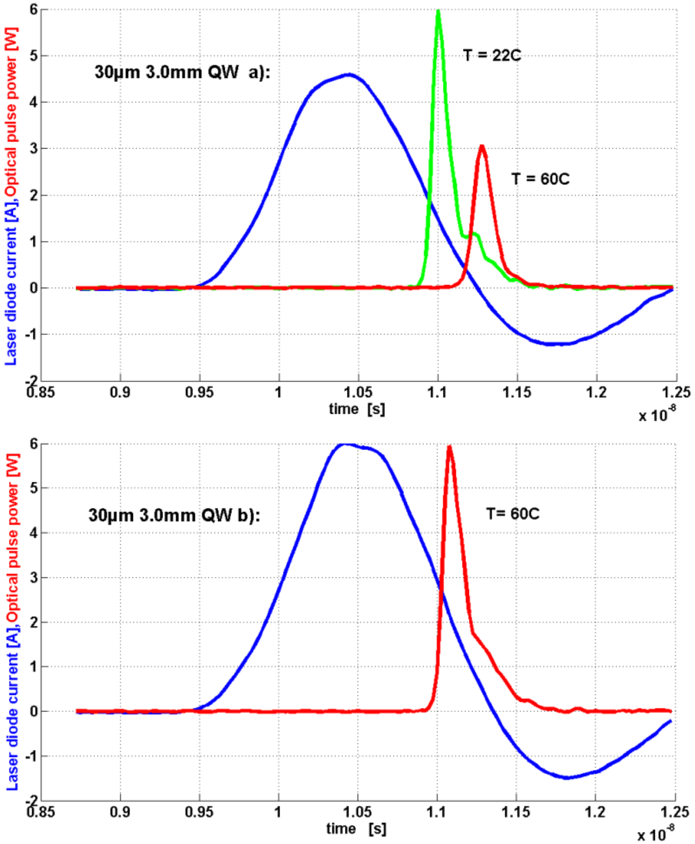
Pulses up to about 10 W peak from a 30 µm stripe, *E* ~ 1 nJ

Saturation of peak power with current due to afterpulsing structure

J. Huikari *et al*, *IEEE J Select.Top. Quantum Electron*, **21** (6), 1501206, 2015

Broad asymmetric waveguide MQW gain switched laser: Experimental performance (3)





- Some deterioration of performance with temperature (threshold increase)
- But can be overcome by relatively modest current increase without deterioration in pulse parameters – and at high currents would be beneficial

J. Huikari *et al*, *IEEE J Select.Top. Quantum Electron*, **21** (6), paper 1501206, 2015

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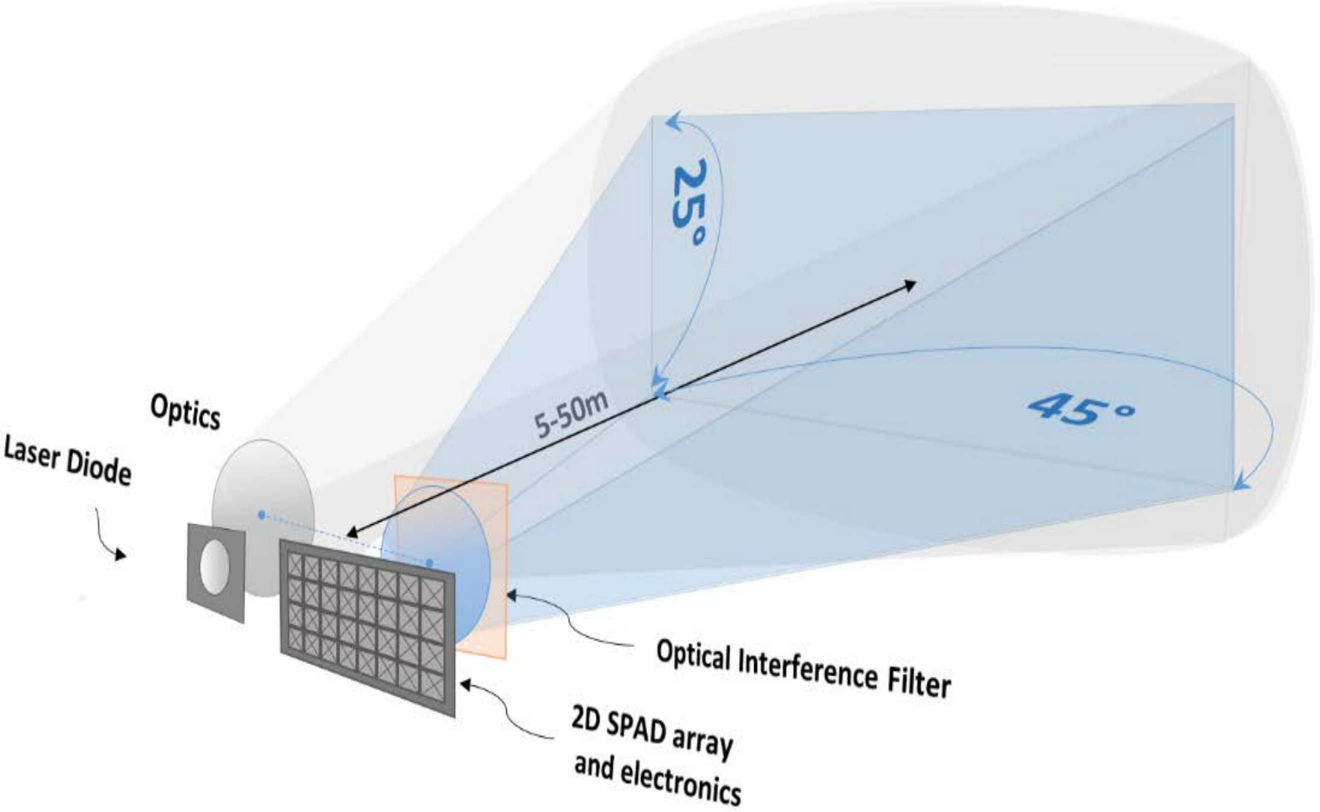
Pulsed TOF with focal plane scanning

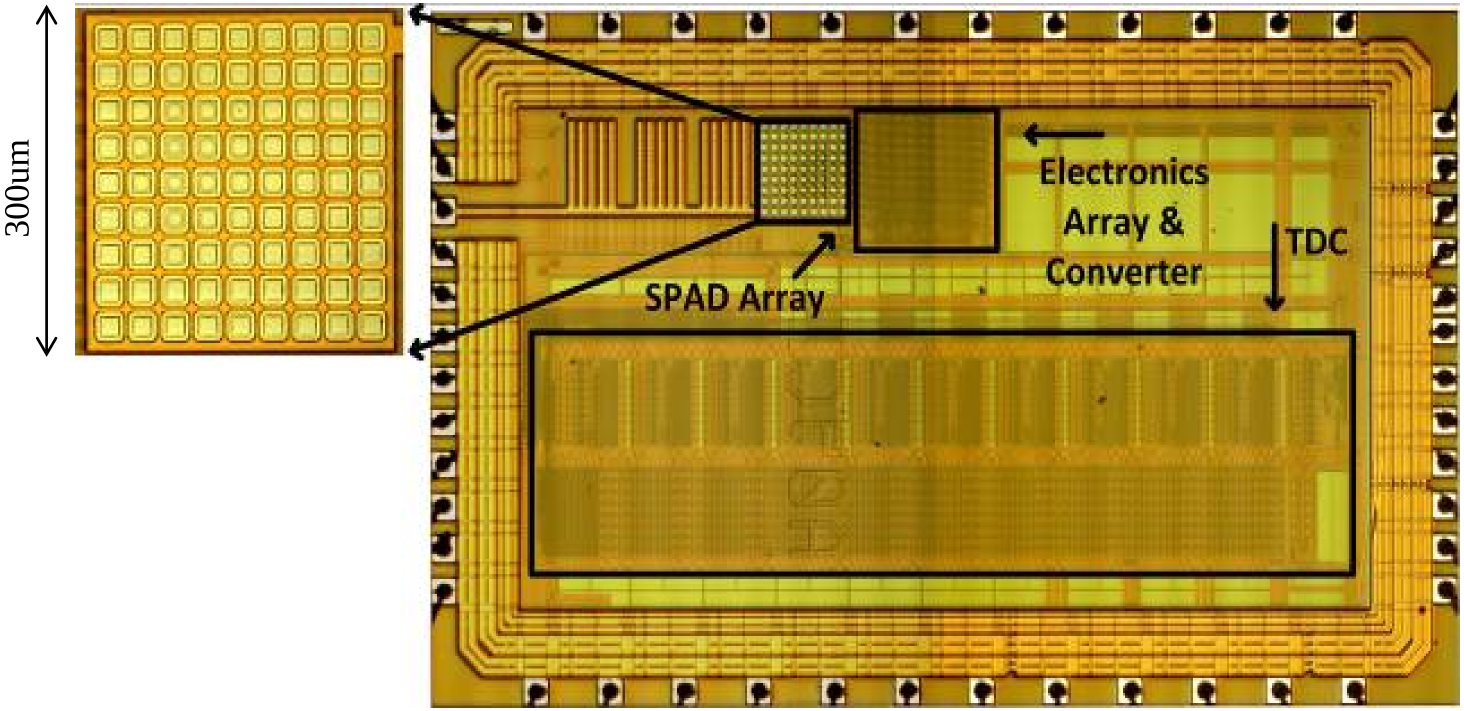


- range 1m..10m..100m
- ”high” spatial resolution
- accuracy ~ cm
- > 5 frames/sec

- The optics ensures a 1-to-1 correspondence between a SPAD in the array and an angle/direction within the field of vision; a fully monolithic, fully digital scanner
- The use of SPADs and short pulses greatly reduces system complexity compared with analogue detection

Receiver: SPAD array + time-to-digital converters

- Proof of concept design with 9 x 9 SPADs and 10 TDC´s
- Electric scan over the detector surface
- SPADs can be switched ON with a 4ns resolution for time gating



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InGaAsP devices for operating at λ~ 1.5 μm

(+) eye – safe range: powers an order of magnitude higher allowed by regulations

(-) Incompatible with Si SPADs: receivers need to be developed alongside lasers (hence immediate application in 1D measurement – in 3D measurements, arrays of SPADs required hence mature integration technology of Si is very attractive)

(-) New laser physics to overcome

(1) Auger recombination:

$$\frac{1}{\tau_n(n)} = \frac{n}{\tau_{nr}} + \frac{Bn^2}{1+n/n_{sp}^{sat}} + Cn^3$$

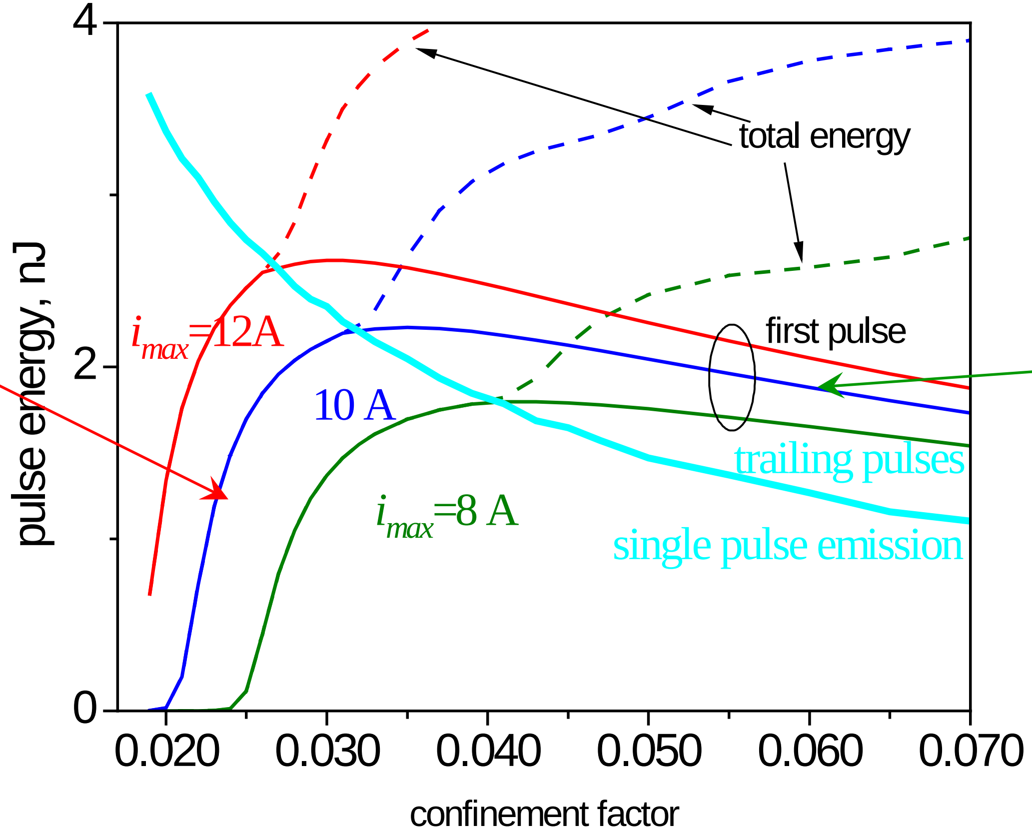
Leads to faster threshold current increase at small confinement:

$$i_{th} = \frac{eV_{active}n_{th}}{\tau_n(n_{th})}$$

(2) Large free-hole absorption (affects output)

Confinement effect on gain-switching in 1.5 μm lasers

Decreased current over threshold

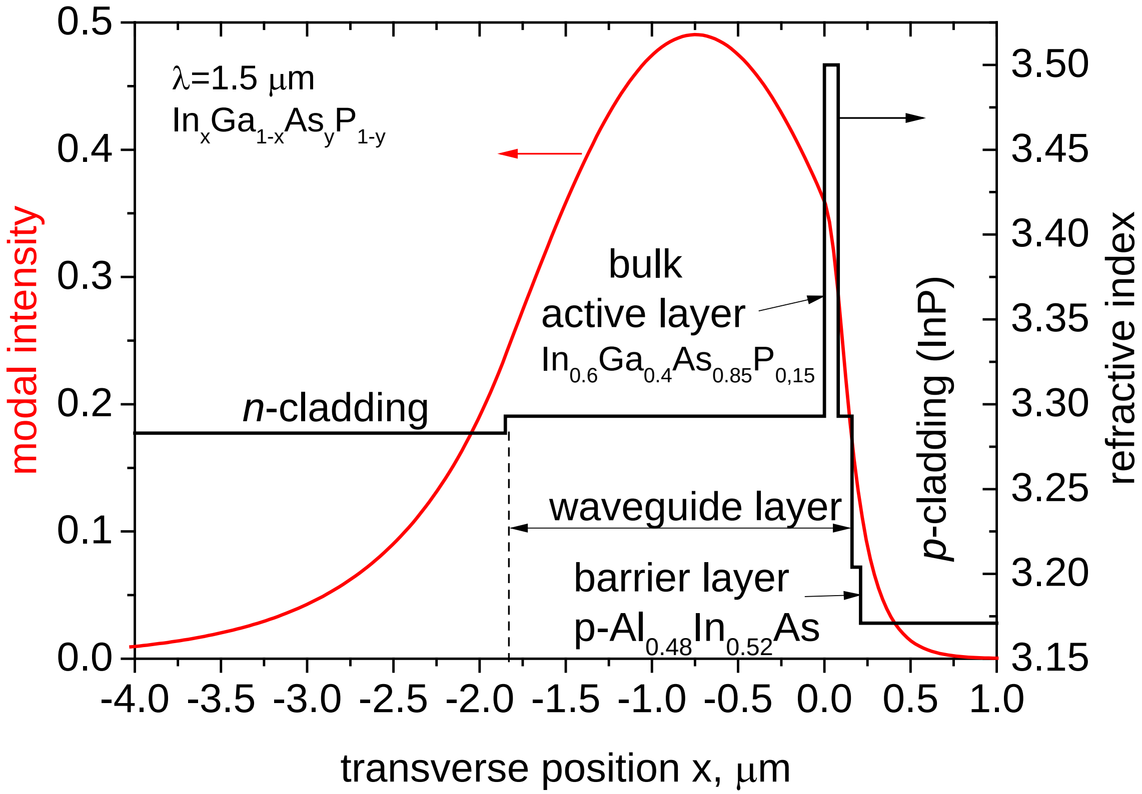


Increased carrier storage

d_{active}= 800 Å

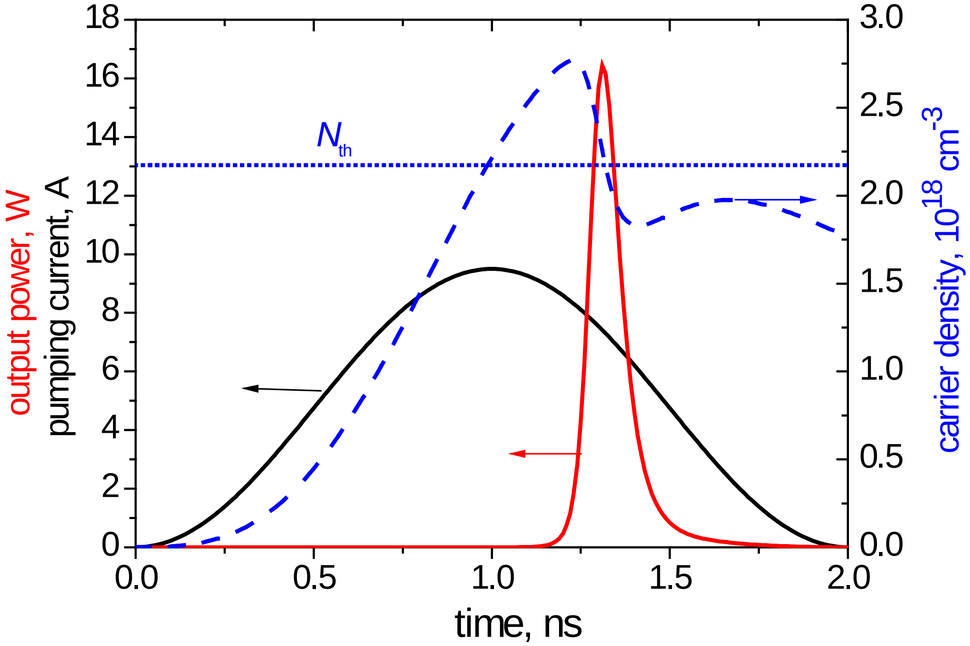
- Improvement of pulse energy by decrease in confinement is modest
- However (moderately) low confinement is still desirable for single-pulse operation

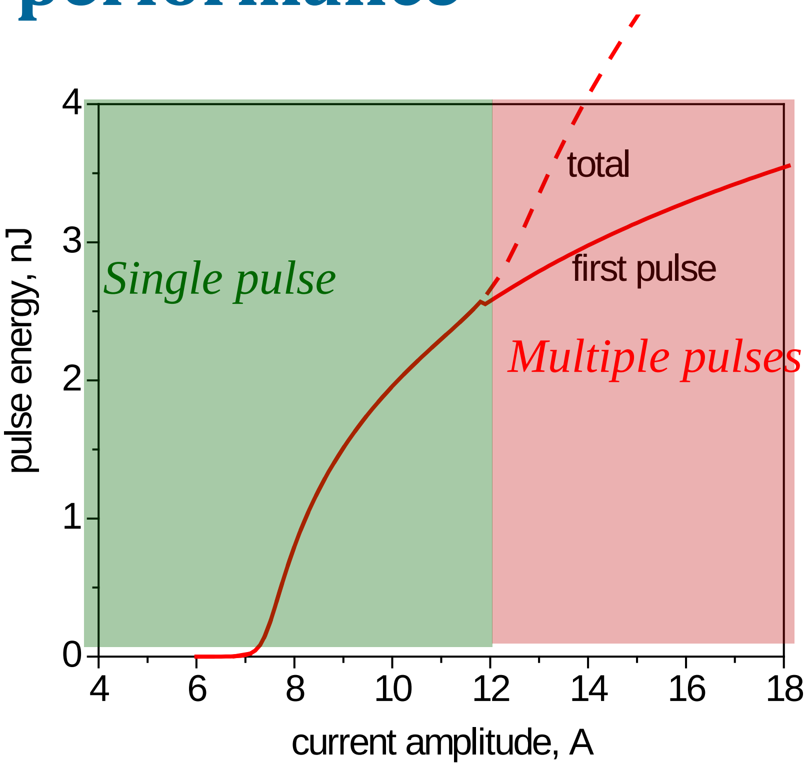
Asymmetric design for a gain-switched λ~ 1.5 μm laser



- bulk active layer, *d* = 500 Å, Γ=0.027 (to keep Auger recombination moderate)
- barrier layer to prevent current leakage

Asymmetric design for a 1.5 µm laser: predicted gain-switching performance





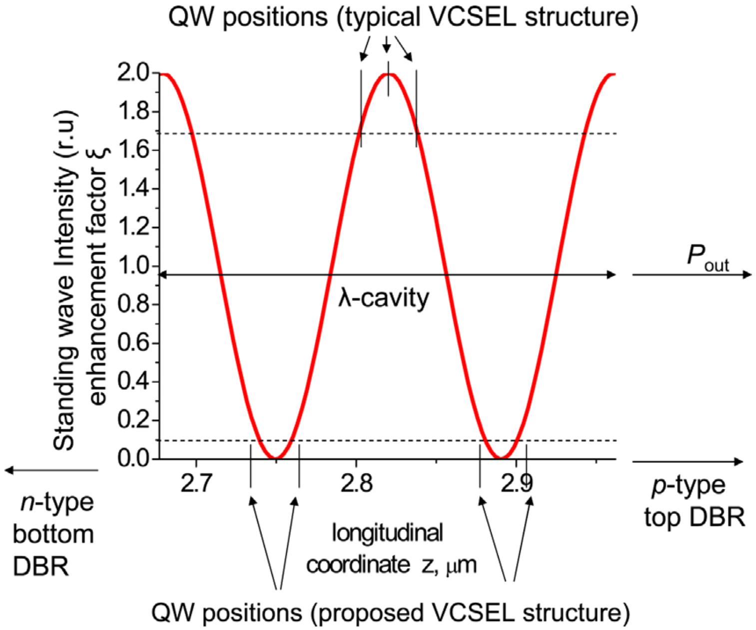
- Pulse peak powers/energies comparable with GaAs/AlGaAs structures
- Single pulse to > 10 A

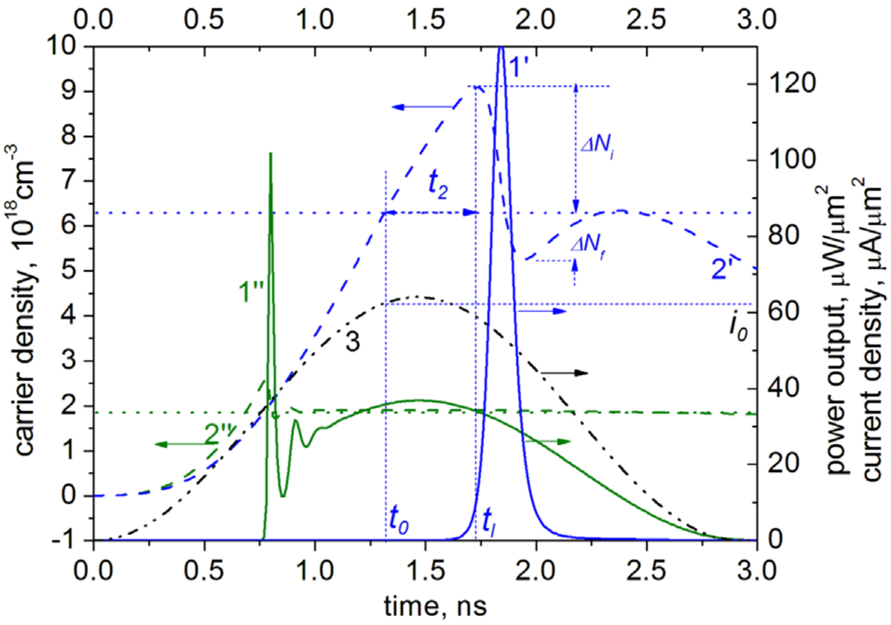
Vertical cavity lasers with increased d/Γ_a

Using a VCSEL array instead of an edge emitter promises good far field, high η_{optic}

$$\Gamma_a^{VCSEL} \approx \frac{d_a}{L_{eff}}\xi$$

ξ – *standing wave factor,* $0 < \xi < 2$





Moving the active layer QWs away

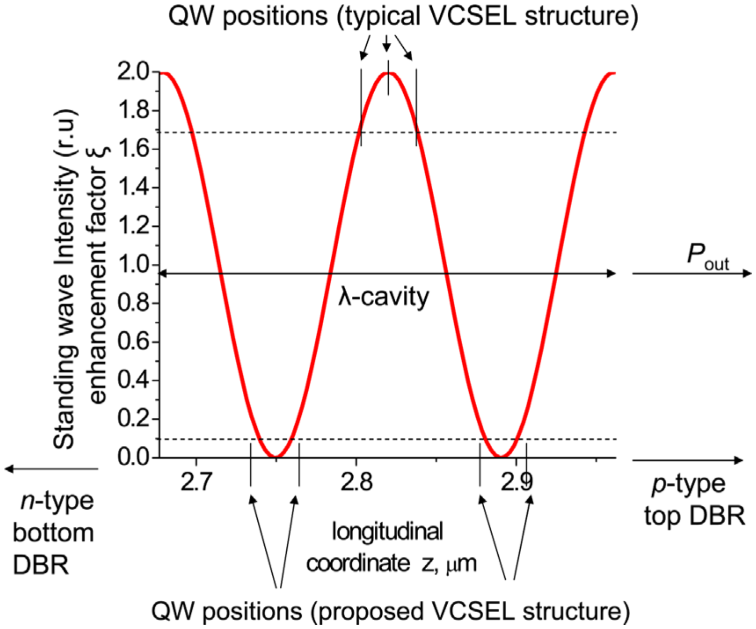
from the antinodes decreases ξ hence Γ_a, enabling short intense pulse generation

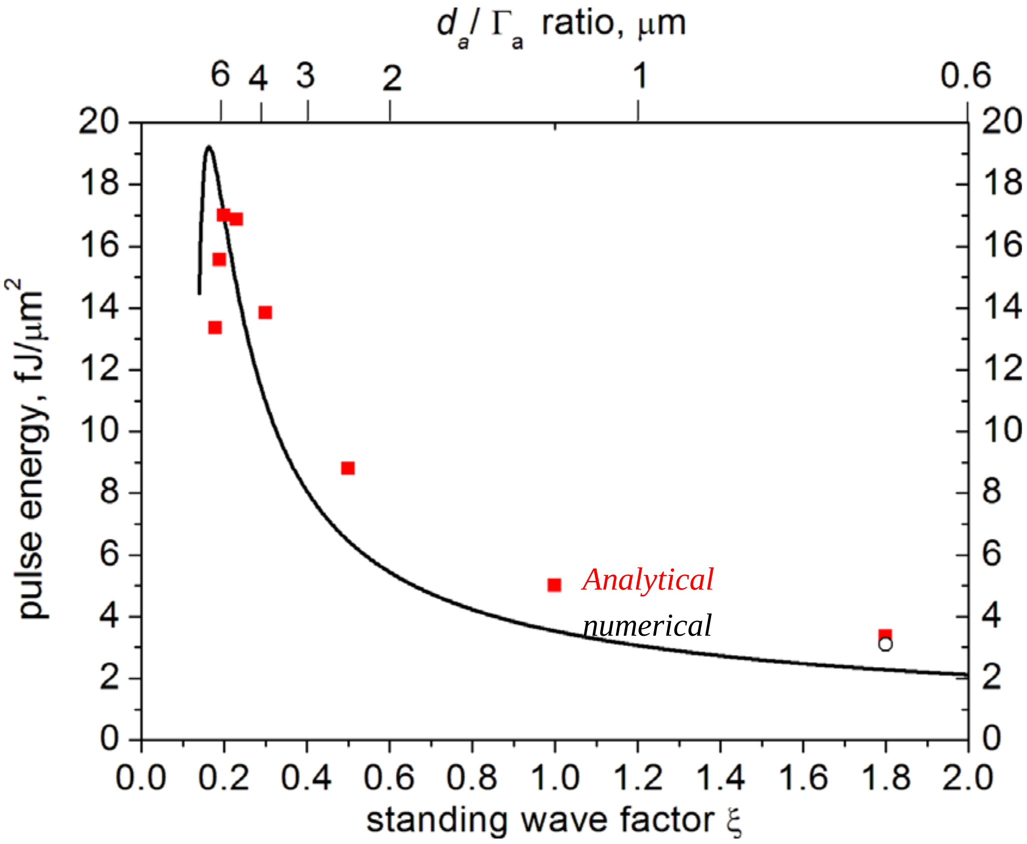
B.S. Ryvkin, E.A.Avrutin, J.T. Kostamovaara, *J. Appl. Phys*. **110**, 123101 (2011)

Vertical cavity lasers with increased d/Γ_a

$$\Gamma_a^{VCSEL} \approx \frac{d_a}{L_{eff}}\xi$$

ξ – standing wave factor, $0< \xi <2$





- Substantial increase in single-pulse energy *per unit area* can be expected – a 2D array of such VCSELs can be a high brightness pulsed source

B.S. Ryvkin, E.A.Avrutin, J.T. Kostamovaara, J. Appl. Phys. **110**, 123101 (2011)

Spectral control/narrowing of laser emission

- All our work so far has been on Fabry-Pérot lasers, hence broad spectra

- Spectral control desirable to minimise background radiation effects ⇒ false triggering

- DFB/monolithic DBR/compound cavity/external grating reflector/VCSEL array ?

  e.g. J. Viheriälä et al. (TUT), Photonics West 2018, paper 10514-41 – P_{peak}=1.6 W source limited at 1550 nm (eye safe)

- Issues:
  - Need inexpensive mass-produceable technology
  - Need design combining the large d/Γ_a and spectral control (e.g. etched grating and a strongly asymmetric waveguide are not a trivial combination).

- True single-frequency operation not needed ⇒ higher order grating may be acceptable

(see next page)

Spatial control of laser emission

- Asymmetric waveguide ensures a single *transverse* mode, but currently we have multiple *lateral* modes (broad stripe laser)
- Control of lateral structure not too big a problem so far, but attractive for efficient beam collimation (improved η_{optic}).
- Possible designs combining spectral and spatial control:
  - VCSEL array?
  - Tapered DBR, possibly with higher order grating, e.g.

A.Klehr *et.al.*, *Photon. Technol. Lett.*, **22**, N10 (2010).

Used for repetitive gain-switching at 1 GHz, 1060 nm

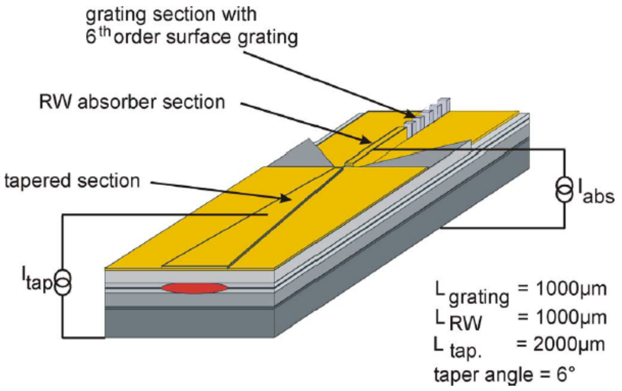


Fig. 1. DBR tapered laser with tapered, absorber and Bragg sections. The active layer (InGaAs QW) extends over all sections.

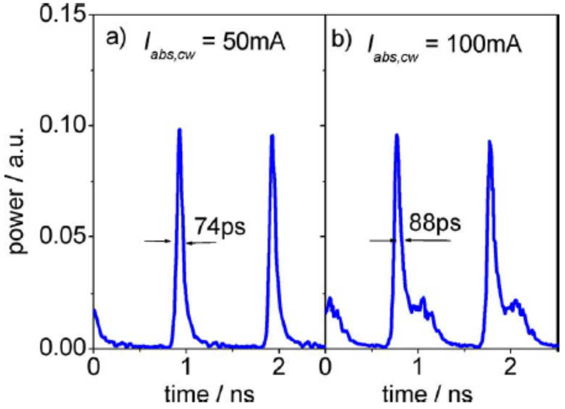


Fig. 5. Time behavior of the generated pulses for (a) $I_{\text{abs,cw}} = 50$ mA and (b) 100 mA at a tapered current of 4 A.

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Conclusions

1. Gain-switched laser diodes are a natural source for time of flight LIDARs with range of tens of metres and centimetre resolution

2. A broad asymmetric waveguide structure with a large equivalent spot size is promising for high energy pulse generation for gain switching and LIDARs; a short saturable absorber further increases single-pulse operation range.

3. A combination of gain switched lasers and SPAD arrays enables precision 3D imaging

4. Improving the spectral and spatial properties of laser emission promises further progress with LIDAR performance

Questions please