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Semiconductor saturable absorber mirrors (SESAMs)

Ursula Keller

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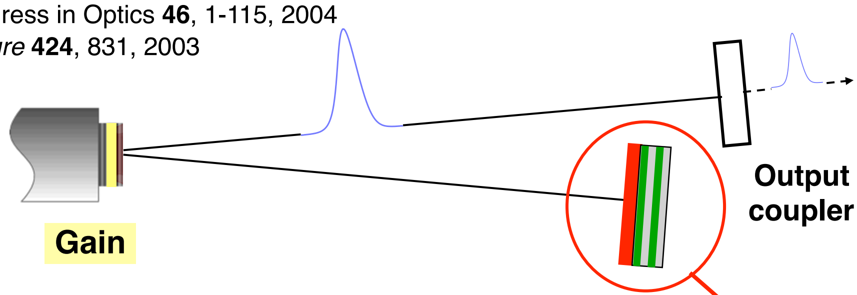
7th EPS-QEOD Europhoton Conference, Aug. 21-26, 2016
Vienna, Austria
Summer School Courses, SCL-3, Monday, Aug. 22, 2016

SESAM technology – ultrafast lasers for industrial application

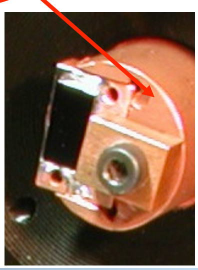
U. Keller et al. *Opt. Lett.* **17**, 505, 1992
IEEE JSTQE **2**, 435, 1996
Progress in Optics **46**, 1-115, 2004
Nature **424**, 831, 2003

SESAM solved Q-switching problem for diode-pumped solid-state lasers



SESAM
SEmiconductor **S**aturable **A**bsorber **M**irror

self-starting, stable, and reliable modelocking of diode-pumped ultrafast solid-state lasers



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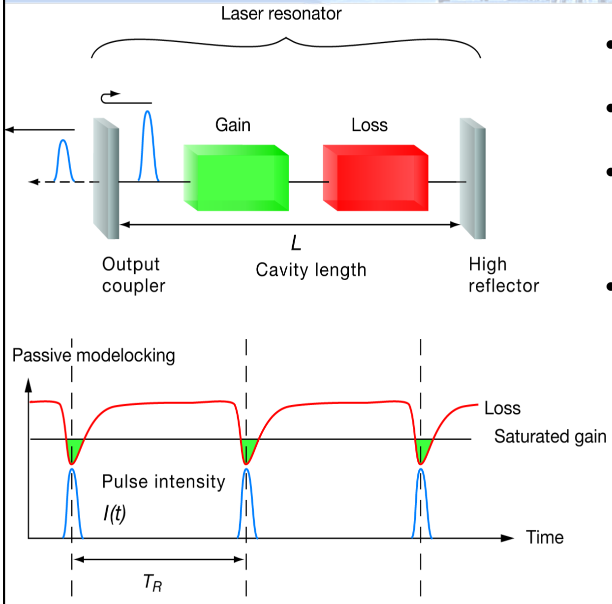
Passively modelocked laser



- Short pulse circulates in cavity (fs-ps)
- High repetition rate pulse train at the output (MHz-GHz)
- Pulse formation process initiated and stabilized by saturable absorber in the laser cavity
- Steady-state pulse parameters: governed by interplay of gain, (saturable) loss, dispersion, Kerr nonlinearity, etc.

⇩

Parameters of absorber need to be chosen to avoid instabilities:

- **Q-switching instabilities** in **solid-state laser gain media**
- **Multiple pulsing instabilities …**

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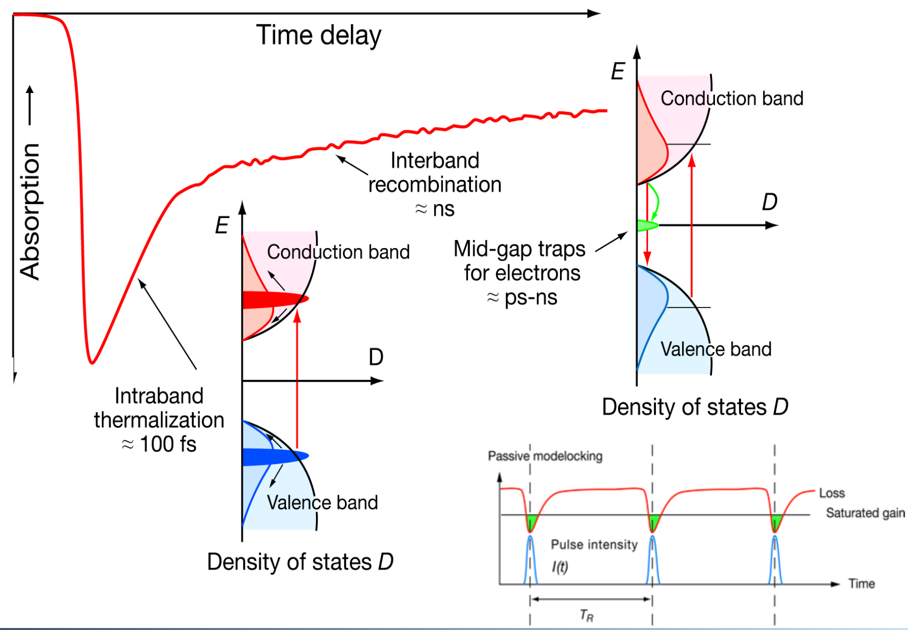
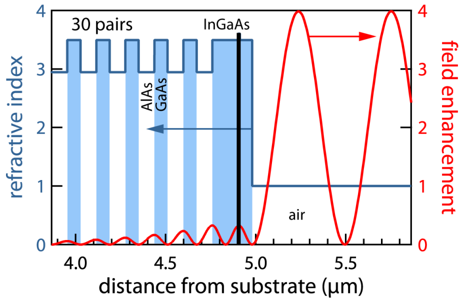
Semiconductor saturable absorber



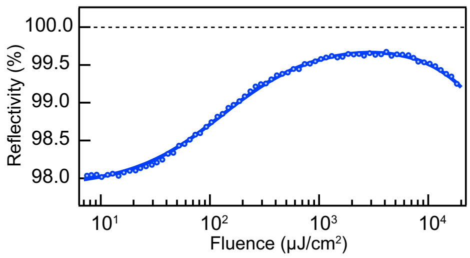
SESAM

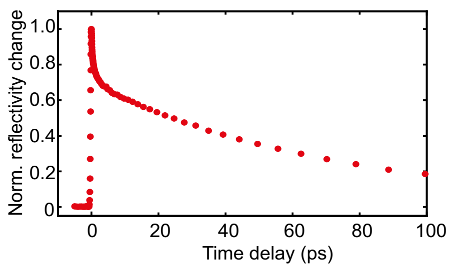
SESAM Semiconductor saturable absorber mirror

U. Keller, et al., *IEEE J. Sel. Top. Quant.* **2**, 435 (1996)



- ✓ Widely tunable absorber parameters (growth conditions, material choice, topsection…) for different types of laser geometries
- ✓ Self-starting, reliable modelocking
- ✓ **Power scalable by increase of mode diameter (constant saturation)**





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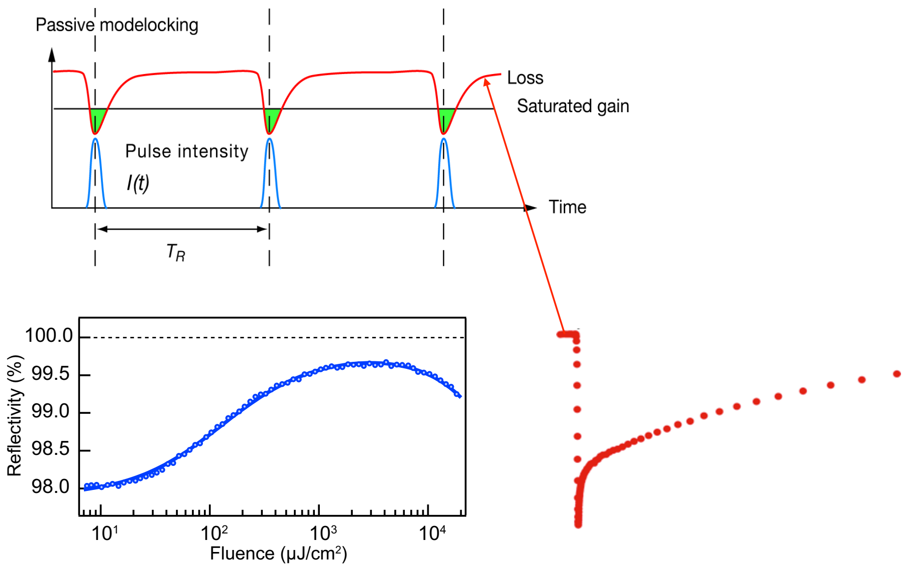
SESAM

SESAM Semiconductor saturable absorber mirror

U. Keller, et al., *IEEE J. Sel. Top. Quant.* **2**, 435 (1996)



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Outline

- Why and how was the SESAM invented?
- Challenge: need fast saturable absorber for shorter pulses
  Solution: Defect management (low temperature growth, AlAs traps, surface traps ...)
- Problem: Q-switching instabilities for passively modelocked solid-state lasers
  Solution: SESAM parameters
  (semiconductor saturable absorber material + mirror design freedom ideal)
- Challenge: SESAM damage
  Solution: Mode size and inverse saturable absorption
- Problem: Need fast saturable absorber for solid-state lasers (with no dynamic gain saturation)
  Solution: Soliton modelocking
- Problem: Pulses so short that position of electric field underneath pulse envelope needs to be stabilized
  Solution: Carrier envelope offset frequency (CEO) stabilization
  ... this solution also enabled the frequency metrology revolution
- Modelocking and frequency metrology: stabilized frequency combs
- Frontier lasers need different SESAM design parameters ... ongoing research.

Ultrafast Laser Physics ETH zürich

ETH zürich

20 years of SESAM – looking back

Appl Phys B (2010) 100: 15–28
DOI 10.1007/s00340-010-4045-3

Appl. Phys. B **100**, 15-28, 2010

Applied Physics B
Lasers and Optics

Ultrafast solid-state laser oscillators: a success story for the last 20 years with no end in sight

U. Keller

How did it all happen?
This is the paper to read ...

Received: 21 April 2010 / Published online: 13 May 2010

20 years of ultrafast solid-state lasers: invited paper

- Why was it assumed that diode-pumped solid-state lasers cannot be passively modelocked?
- How was the SESAM invented?
- State-of-the-art performance and future outlook.

Ultrafast Laser Physics ETH zürich

20 years of SESAM

April 1, 1992 / Vol. 17, No. 7 / OPTICS LETTERS 505

Solid-state low-loss intracavity saturable absorber for Nd:YLF lasers: an antiresonant semiconductor Fabry–Perot saturable absorber

U. Keller, D. A. B. Miller, G. D. Boyd, T. H. Chiu, J. F. Ferguson, and M. T. Asom

AT&T Bell Laboratories, Crawfords Corner Road, Holmdel, New Jersey 07733

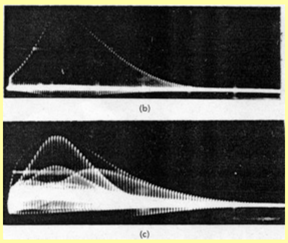
Received November 26, 1991

We introduce a new low-loss fast intracavity semiconductor Fabry–Perot saturable absorber operated at antiresonance both to start and sustain stable mode locking of a cw-pumped Nd:YLF laser. We achieved a 3.3-ps pulse duration at a 220-MHz repetition rate. The average output power was 700 mW with 2 W of cw pump power from a Ti:sapphire laser. At pump powers of less than 1.6 W the laser self-Q switches and produces 4-ps pulses within a 1.4-μs Q-switched pulse at an ≈150-kHz repetition rate determined by the relaxation oscillation of the Nd:YLF laser. Both modes of operation are stable. In terms of coupled-cavity mode locking, the intracavity antiresonant Fabry–Perot saturable absorber corresponds to monolithic resonant passive mode locking.

First SESAM (first design called A-FPSA)
April 1, 1992 (submitted Nov. 26, 1991)

Ultrashort pulse generation with modelocking

A. J. De Maria, D. A. Stetser, H. Heynau
Appl. Phys. Lett. **8**, 174, 1966



Nd:glass
first passively modelocked laser
Q-switched modelocked

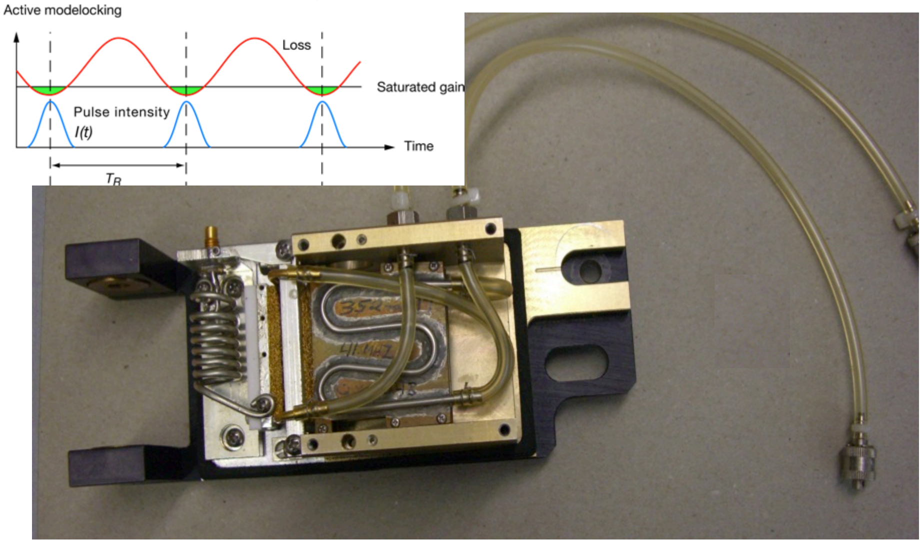
Q-switching problem in passively modelocked solid-state lasers:

- active modelocking for solid-state lasers
- dye lasers solved the problem

1960 1970 1980 1990 2000
Year

Flashlamp-pumped solid-state lasers

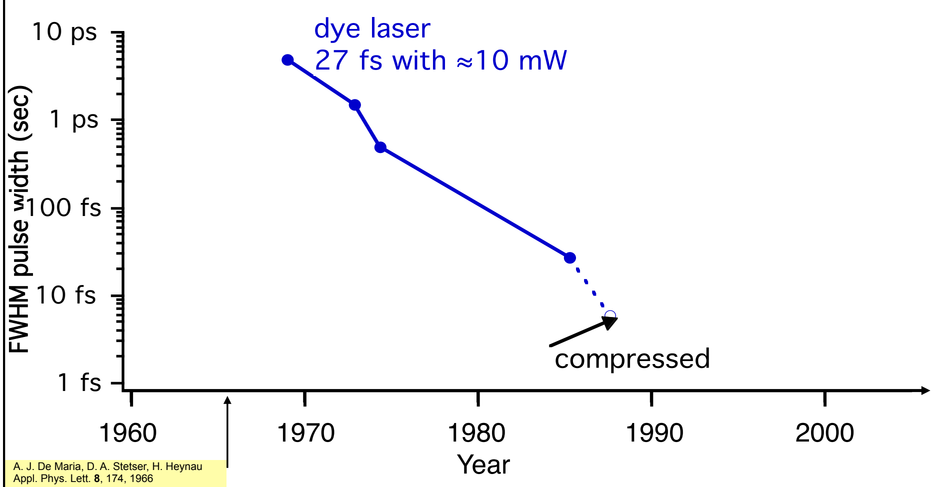
Active Modelocking



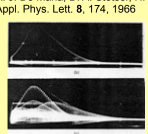
acousto-optic loss modulator

needs RF power and water cooling

Ultrashort pulse generation with modelocking



A. J. De Maria, D. A. Stetser, H. Heynau
Appl. Phys. Lett. **8**, 174, 1966



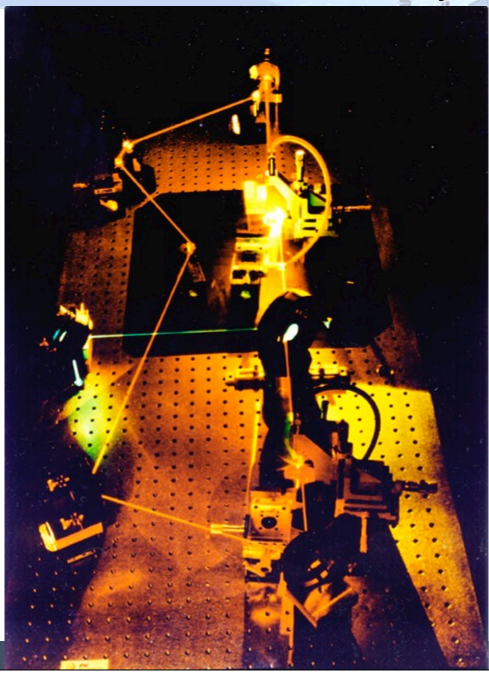
Nd:glass
first passively modelocked laser
Q-switched modelocked

E. P. Ippen, C. V. Shank et al, Appl. Phys. Lett. 21, 348, 1972

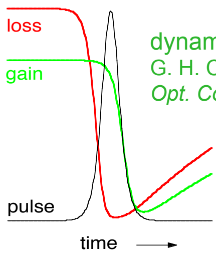
J. A. Valdmanis et al., Opt. Lett. 10, 131, 1985 (27 fs)

R. L. Fork et al., Opt. Lett. 12, 483, 1987 (6 fs)

CPM dye laser



Ring laser
Colliding pulse modelocked (CPM) dye laser:
Gain: Rhodamine 6G
Saturable absorber: DODCI
Center wavelength: ≈620 nm
Typical pulse duration: >27 fs
Typical average power: a few 10 mW
J. A. Valdmanis et al.,
Opt. Lett. **10**, 131, 1985 (27 fs CPM)

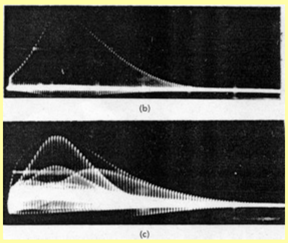


dynamic gain saturation
G. H. C. New
Opt. Commun. **6**, 188, 1972

Ursula Keller, Ph.D. student at Stanford
1986 Summer Student at Bell Labs, NJ

Ultrashort pulse generation with modelocking

A. J. De Maria, D. A. Stetser, H. Heynau
Appl. Phys. Lett. **8**, 174, 1966



200 ns/div
50 ns/div

Nd:glass
first passively modelocked laser
Q-switched modelocked

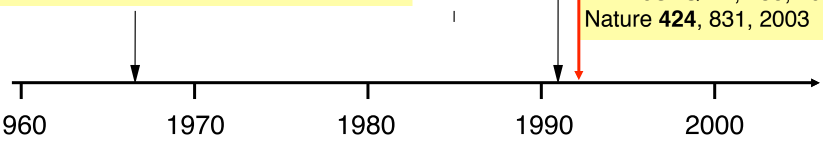
Q-switching instabilities continued to be a problem until 1992

SESAM
First passively modelocked (diode-pumped) solid-state laser without Q-switching

U. Keller et al.
Opt. Lett. **17**, 505, 1992

IEEE JSTQE **2**, 435, 1996
Nature **424**, 831, 2003

KLM

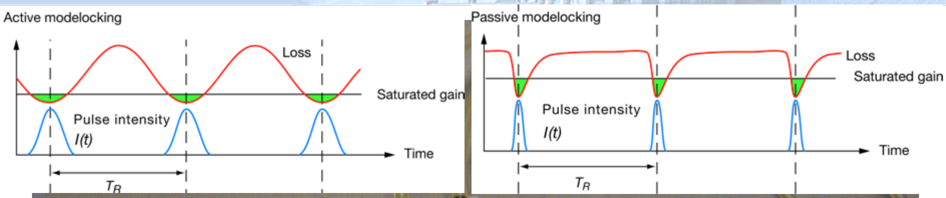


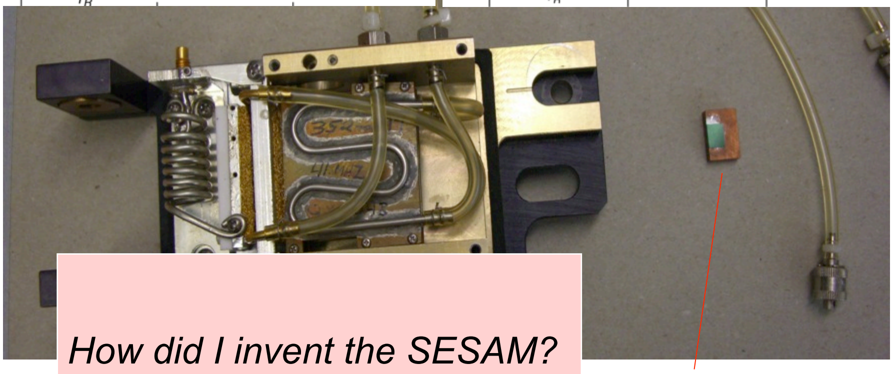
Flashlamp-pumped solid-state lasers

Diode-pumped solid-state lasers
(first demonstration 1963)

ETH zürich

Innovation: before and after





How did I invent the SESAM?

SESAM modelocker

ac

ne

Thank you to Stanford, Bell Labs and ETH Zurich

LELAND STANFORD JUNIOR UNIVERSITY · DIE LUFT DER FREIHEIT WEHT · 1891

AT&T Bell Laboratories

ETH Eidgenössische Technische Hochschule Zürich
Swiss Federal Institute of Technology Zurich

Stanford University

Ph.D. student

1985-1989

laser physics

ultrafast measurement techniques

microwave measurement tools

Bell Labs, Holmdel

MTS

1989-1993

+ access to state-of-the-art semiconductor materials (MBE)

ETH Zurich

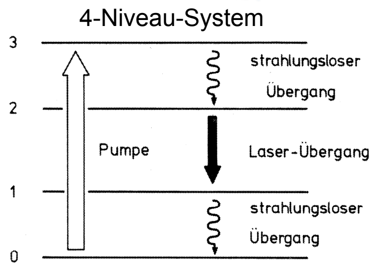
tenured Professor in Physics

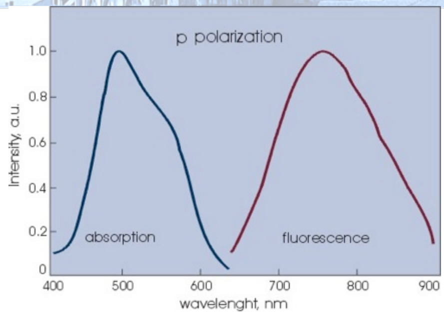
since 1993

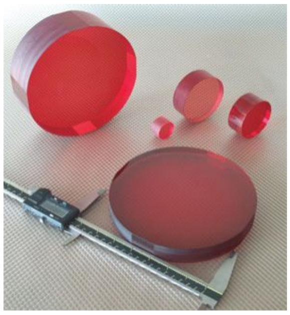
+ resources to be fully empowered

Enabled interdisciplinary approach with the combination of solid-state lasers, semiconductor physics, and microwave measurement techniques.

Ti^{3+}:Saphir Laser

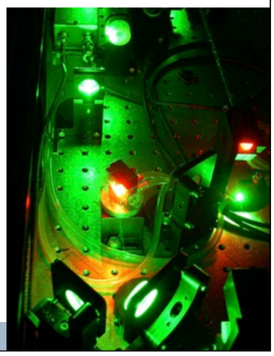






Ti:Saphir Laser
1982

Peter Moulton
MIT Lincoln Lab



Two experiments that should not have worked ...

"Magic Modelocking"

Postdeadline Paper CLEO 1990
Nr. CPDP10

"modelocked Ti:sapphire laser without an absorber inside the cavity"
... should not work!

Published result later in:
D. E. Spence, P. N. Kean, W. Sibbett, *Optics Lett.* **16**, 42, 1991

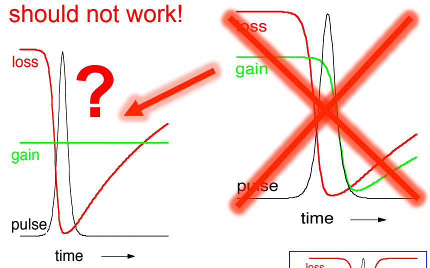
Explained modelocking as a "coupled cavity modelocking effect" between two transverse modes

"CPM Ti:sapphire laser"

Postdeadline Paper Ultrafast Phenomena 1990, Nr. PD11

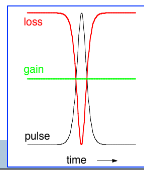
Y. Ishida, N. Sarukura, H. Nakano

"used a dye saturable absorber inside the CPM Ti:sapphire laser"
... should not work!



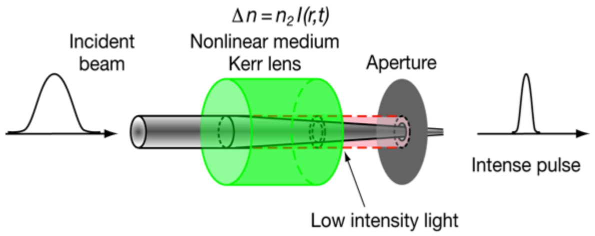
Both of them explained later by KLM by Keller et al.

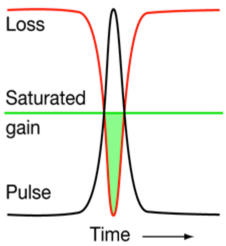
Optics Lett. **16**, 1022, 1991 | *IEEE JQE* **28**, 2123, 1992



Kerr Lens Modelocking (KLM)

First Demonstration: D. E. Spence, P. N. Kean, W. Sibbett, *Optics Lett.* **16**, 42, 1991
Explanation: U. Keller et al., *Optics Lett.* **16**, 1022, 1991





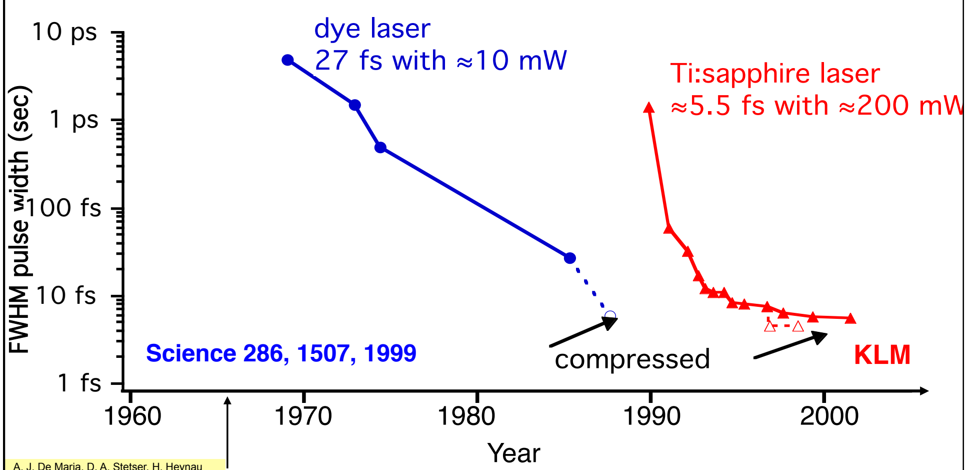
Advantages of KLM

- very fast thus shortest pulses
- very broadband thus broader tunability

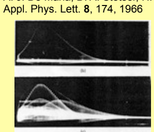
Disadvantages of KLM

- not self-starting
- critical cavity adjustments (operated close to the stability limit)
- saturable absorber coupled to cavity design (limited application)

Ultrashort pulse generation with modelocking



A. J. De Maria, D. A. Stetser, H. Heynau
Appl. Phys. Lett. **8**, 174, 1966



Nd:glass
first passively modelocked laser
Q-switched modelocked

Kerr lens modelocking (KLM):
discovered - initially not understood ("magic modelocking")
D. E. Spence, P. N. Kean, W. Sibbett, *Opt. Lett.* 16, 42, 1991
KLM mechanism explained for the first time:
U. Keller et al., *Opt. Lett.* 16, 1022, 1991

Why did the Sibbett group explain their results as a “coupled modelocking effect”?

Remember the mind set at that time was:

Passive modelocking of solid-state laser does not work!

... but there was the soliton laser from Linn Mollenauer

Soliton Laser by Linn Mollenauer

1984

January 1984 / Vol. 9, No. 1 / OPTICS LETTERS 13

The soliton laser

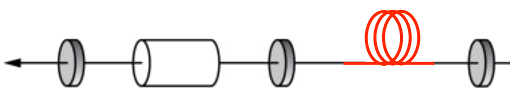
L. F. Mollenauer and R. H. Stolen

Bell Laboratories, Holmdel, New Jersey 07733

Received October 17, 1983; accepted October 28, 1983

By incorporating a length of single-mode, polarization-preserving fiber into the feedback loop of a mode-locked color-center laser ($\lambda \sim 1.4$–$1.6\ \mu$m), we have created a device that we call the soliton laser. Pulse width (2.0 to 0.21 psec obtained to date) is determined by fiber length, in accordance with $N = 2$ soliton behavior. Production of <50-fsec-wide pulses is indicated for compression in an additional, external fiber.

Coupled cavity



fiber with negative dispersion (GDD < 0)

soliton pulse compression in coupled cavity with shortens pulse in main cavity

Coupled Cavity Modelocking by Wilson Sibbett

1989

January 1, 1989 / Vol. 14, No. 1 / OPTICS LETTERS 39

Enhanced mode locking of color-center lasers

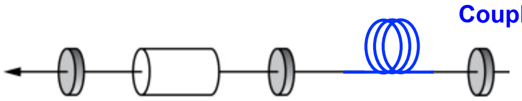
P. N. Kean, X. Zhu, D. W. Crust, R. S. Grant, N. Langford, and W. Sibbett

Department of Physics and Astronomy, University of St. Andrews, St. Andrews, Fife KY16 9SS, Scotland

Received July 18, 1988; accepted October 14, 1988

A significant enhancement in the mode locking of a KCl:Tl color-center laser has been observed when a length of optical fiber having positive group-velocity dispersion was incorporated within an external control cavity. Pulse durations of ~260 fsec were obtained by this method, representing a compression factor ~60× that with the color-center laser alone. Similar results have also been observed with an InGaAsP semiconductor diode amplifier as the nonlinear element within the control cavity.

Coupled cavity modelocking (CCM)



fiber with **positive** dispersion (GDD > 0)

Dispersive pulse broadening in coupled cavity! How should that shorten pulse in main cavity?

Explanation with **APM (additive pulse modelocking)**:
E. P. Ippen, H. A. Haus, L. Y. Liu, *J. Opt. Soc. Am. B* **6**, 1736, 1989
Pulse is broadened yes, ... but SPM makes an intensity dependent phase shift, which leads to constructive interference at the peak and destructive inteference in the wings with the pulse from the main cavity. This gives a pulse shortening effect of the coupled cavity.

Coupled Cavity Modelocking by "Blow & Wood"

1988 K. J. Blow and D. Wood Vol. 5, No. 3/March 1988/J. Opt. Soc. Am. B 629

Mode-locked lasers with nonlinear external cavities

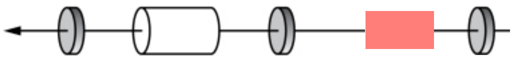
K. J. Blow and David Wood

British Telecom Research Laboratories, Martlesham Heath, Ipswich IP5 7RE, UK

Received August 31, 1987; accepted November 9, 1987

A nonlinear element, when introduced into an external cavity, is shown to improve the mode locking of lasers. Mode locking is achieved by inducing coupling between the cavity modes, thus permitting more efficient transmission of phase information. We begin by discussing a phenomenological laser model for homogeneously broadened systems. The model laser is coupled to an external cavity and contains a nonlinear element. The returning pulse from this external cavity is then mixed with a circulating pulse in the laser at the output mirror. We have considered two nonlinear elements, a saturable absorber and a saturable amplifier. Although these elements have quite different pulse-shaping effects, they both cause considerable improvement in mode-locked performance.

Coupled cavity



"any nonlinear element in the coupled cavity should shorten the pulse"

theoretical prediction with numerical modeling ... physical insight was missing

Coupled Cavity Modelocking by Ursula Keller

1990

December 1, 1990 / Vol. 15, No. 23 / OPTICS LETTERS 1377

Coupled-cavity resonant passive mode-locked Ti:sapphire laser

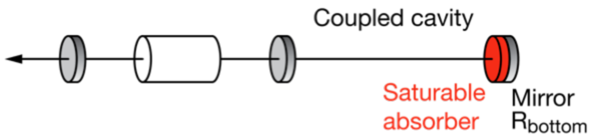
U. Keller, W. H. Knox, and H. Roskos

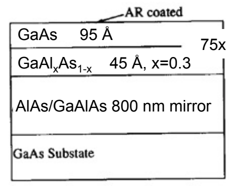
AT&T Bell Laboratories, Crawfords Corner Road, Holmdel, New Jersey 07733

Received June 21, 1990; accepted September 26, 1990

We use a nonlinear quantum-well reflective sample in a coupled-cavity configuration for resonant passive mode locking of a Ti:sapphire laser, producing tunable pulses as short as 2 psec. Pulses of less than 10-psec duration are observed over a 50-nm wavelength tuning range using a single-quantum-well reflector, over approximately 2 mm of external cavity length detuning. Stable mode-locked pulse trains are obtained without active cavity length control; however, the optical spectrum depends on the phase. We generate up to the sixth harmonic of the fundamental repetition rate, at 1.2 GHz, by simply decreasing the external cavity length.

Resonant passive modelocking (RPM)



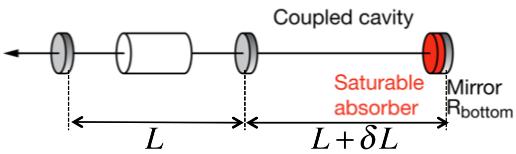


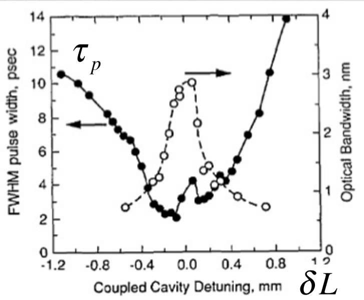
semiconductor saturable absorber (*"borrowed from my office neighbour Keith Goosen"*)
pulse compression in coupled cavity which shortens pulse in main cavity

Coupled Cavity Modelocking by Ursula Keller

1990

Resonant passive modelocking (RPM)





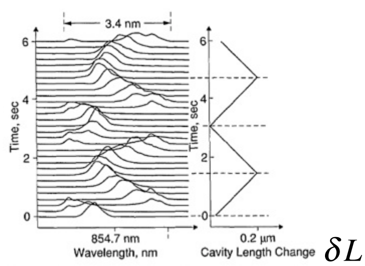
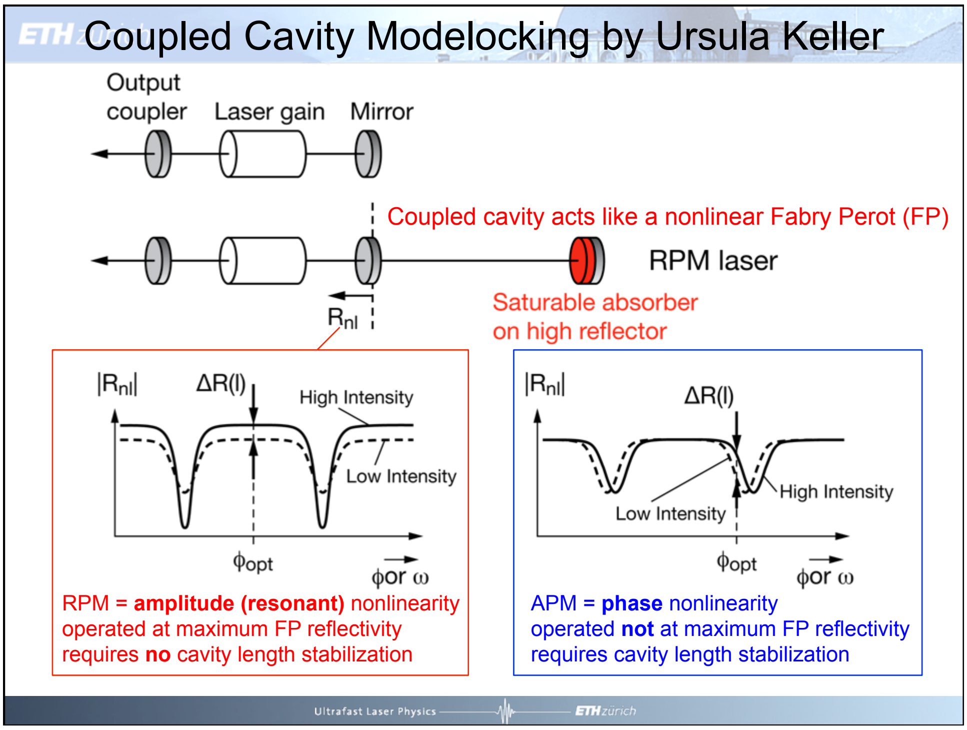


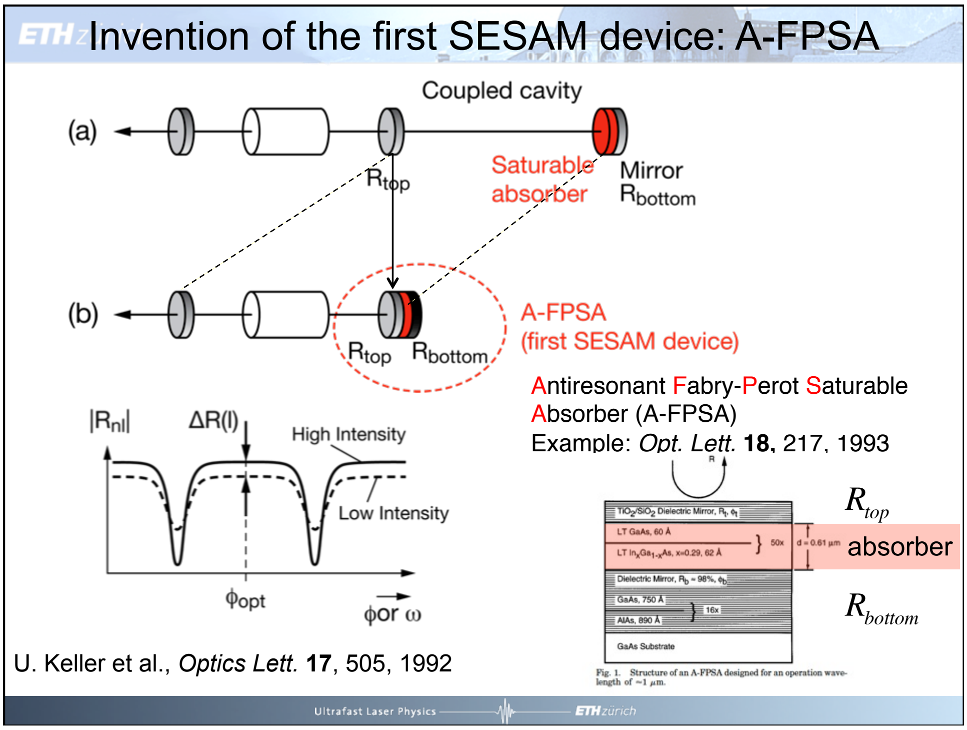
Fig. 3. Optical self-frequency shift versus the external cavity length detuning that ensures coherent superposition of the pulses at the coupling mirror.

Surprise:

- **no** active cavity length stabilization was necessary
- modelocking was stable even with large cavity length detuning δL

U. Keller et al., *Optics Lett.* **15**, 1377, 1990

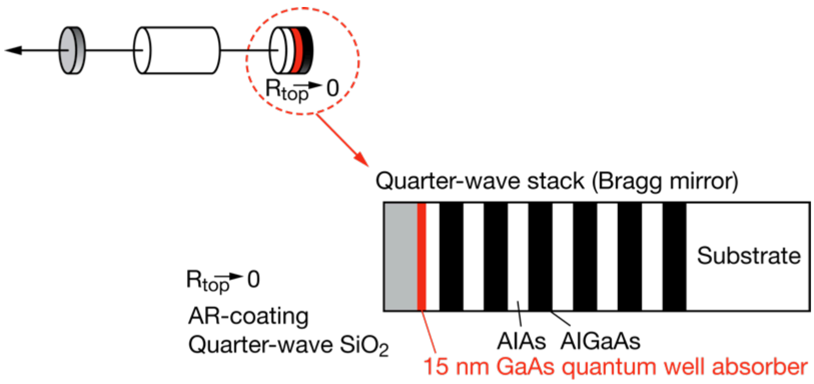

Coupled Cavity Modelocking by Ursula Keller
Output coupler
Laser gain
Mirror
Coupled cavity acts like a nonlinear Fabry Perot (FP)
RPM laser
Saturable absorber on high reflector
Rnl
|Rnl|
ΔR(I)
High Intensity
Low Intensity
φopt
φor ω
RPM = amplitude (resonant) nonlinearity
operated at maximum FP reflectivity
requires no cavity length stabilization
|Rnl|
ΔR(I)
High Intensity
Low Intensity
φopt
φor ω
APM = phase nonlinearity
operated not at maximum FP reflectivity
requires cavity length stabilization
Ultrafast Laser Physics
ETH zürich


Invention of the first SESAM device: A-FPSA
Coupled cavity
(a)
Rtop
Saturable absorber
Mirror
Rbottom
(b)
Rtop
Rbottom
A-FPSA
(first SESAM device)
Antiresonant Fabry-Perot Saturable Absorber (A-FPSA)
Example: Opt. Lett. 18, 217, 1993
|Rnl|
ΔR(I)
High Intensity
Low Intensity
φopt
φor ω
Rtop
absorber
Rbottom
GaAs Substrate
U. Keller et al., Optics Lett. 17, 505, 1992
Ultrafast Laser Physics
ETH zürich

Scaling A-FPSA towards a single QW SESAM

1995

Adjustable parameter: top reflector



Single 15 nm GaAs quantum well embedded inside a Bragg mirror

L. R. Brovelli et al., *Electron. Lett.*, vol. 31, 287, 1995

20 years of SESAM

1996

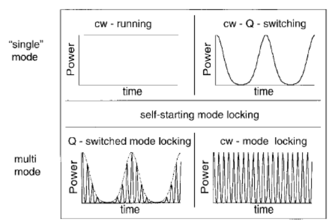
IEEE JOURNAL OF SELECTED TOPICS IN QUANTUM ELECTRONICS, VOL. 2, NO. 3, SEPTEMBER 1996 435

Semiconductor Saturable Absorber Mirrors (SESAM's) for Femtosecond to Nanosecond Pulse Generation in Solid-State Lasers

Ursula Keller, *Member, IEEE*, Kurt J. Weingarten, *Member, IEEE*, Franz X. Kärtner, Daniel Kopf, Bernd Braun, Isabella D. Jung, Regula Fluck, Clemens Hönninger, Nicolai Matuschek, and Juerg Aus der Au

(Invited Paper)

Abstract—Intracavity semiconductor saturable absorber mirrors (SESAM's) offer unique and exciting possibilities for passively pulsed solid-state laser systems, extending from Q-switched pulses in the nanosecond and picosecond regime to mode-locked pulses from 10's of picoseconds to sub-10 fs. This paper reviews the design requirements of SESAM's for stable pulse generation in both the mode-locked and Q-switched regime. The combination of device structure and material parameters for SESAM's provide sufficient design freedom to choose key parameters such as recovery time, saturation intensity, and saturation fluence, in a compact structure with low insertion loss. We have been able to demonstrate, for example, passive modelocking (with no Q-switching) using an intracavity saturable absorber in solid-state lasers with long upper state lifetimes (e.g., 1-μm neodymium transitions), Kerr lens modelocking assisted with pulsewidths as short as 6.5 fs from a Ti:sapphire laser—the shortest pulses ever produced directly out of a laser without any external pulse



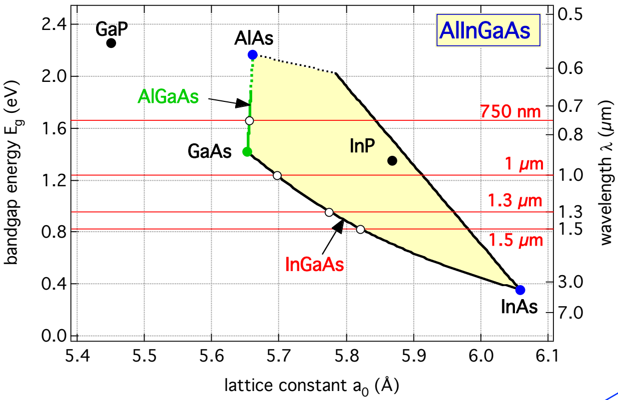
...t modes of operation of a laser with a saturable absorber. ...typically occurs with much longer pulses and lower pulse ...han CW mode-locking.

..., Q-switched modelocking behavior [5]–[9]. In ...iconductor absorbers have an intrinsic bitemporal

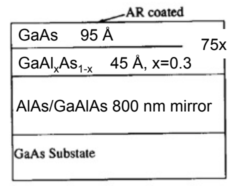
Introduction of the ackronym: SESAM
Invited review article
September 1996, IEEE JSTQE

Moving from Ti:sapphire to diode-pumped ss-laser

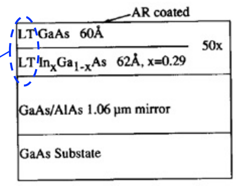
was not trivial .... why?



Ti:sapphire laser
@ 800 nm
Opt. Lett. **15**, 1377, 1990



Nd:YLF laser
@ 1.064 µm
IEEE JQE **28**, 1710, 1992



LT = low temperature
MBE growth

Moving from Ti:sapphire to diode-pumped ss-laser

390 OPTICS LETTERS / Vol. 16, No. 6 / March 15, 1991

Coupled-cavity resonant passive mode-locked Nd:yttrium lithium fluoride laser

U. Keller and T. K. Woodward
AT&T Bell Laboratories, Holmdel, New Jersey 07733
D. L. Sivco and A. Y. Cho
AT&T Bell Laboratories, Murray Hill, New Jersey 07974

1991

RPM modelocked Nd:YLF

April 1, 1992 / Vol. 17, No. 7 / OPTICS LETTERS 505

Solid-state low-loss intracavity saturable absorber for Nd:YLF lasers: an antiresonant semiconductor Fabry–Perot saturable absorber

U. Keller, D. A. B. Miller, G. D. Boyd, T. H. Chiu, J. F. Ferguson, and M. T. Asom
AT&T Bell Laboratories, Crawfords Corner Road, Holmdel, New Jersey 07733

1992

A-FPSA modelocked Nd:YLF

Nd:YLF laser pumped with Ti:sapphire laser

640 OPTICS LETTERS / Vol. 18, No. 8 / April 15, 1993

Passively mode-locked diode-pumped solid-state lasers that use an antiresonant Fabry–Perot saturable absorber

K. J. Weingarten
Lightwave Electronics Corporation, 1161 San Antonio Road, Mountain View, California 94043
U. Keller, T. H. Chiu, and J. F. Ferguson
AT&T Bell Laboratories, Crawfords Corner Road, Holmdel, New Jersey 07733

1993

"mailed A-FPSA to California"

A-PFSA modelocked diode-pumped Nd:YLF and Nd:YAG laser

It also works to modelock fibers ...

1993

1532 OPTICS LETTERS / Vol. 18, No. 18 / September 15, 1993

Self-starting diode-pumped femtosecond Nd fiber laser

M. H. Ober and M. Hofer

Abteilung Quantenelektronik, Technische Universität Wien, Gusshausstrasse 27/359/4, A-1040 Vienna, Austria

U. Keller

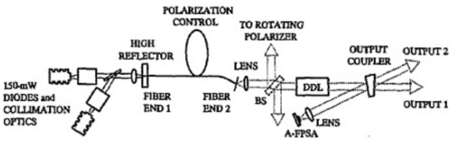
Institute of Quantum Electronics, Swiss Federal Institute of Technology (ETH), CH-8093 Zürich, Switzerland

T. H. Chiu

AT&T Bell Laboratories, Crawfords Corner Road, Holmdel, New Jersey 07701

Received March 26, 1993

A self-starting passively mode-locked diode-pumped neodymium fiber laser with a semiconductor antiresonant Fabry–Perot saturable absorber (A-FPSA) is demonstrated for the first time to our knowledge. Mode locking can be initiated and maintained by the semiconductor absorber, and pulse durations down to 260 fs are routinely obtained. Alternatively, shorter pulses (60 fs) were generated by exploitation of nonlinear polarization evolution in the fiber (in combination with a stronger pump source) where the A-FPSA simply initiates the pulse-forming process.

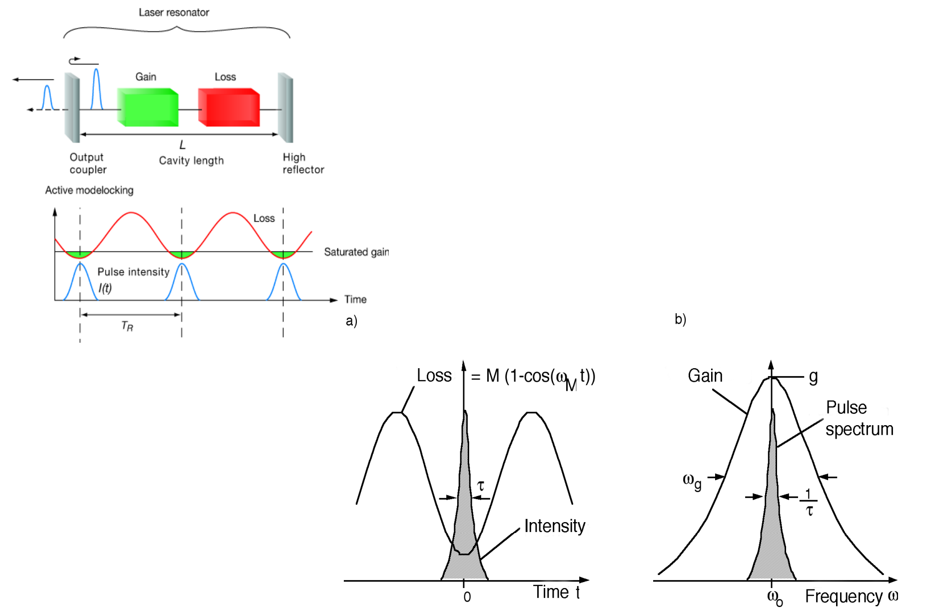


"carried an A-FPSA to TU Vienna"

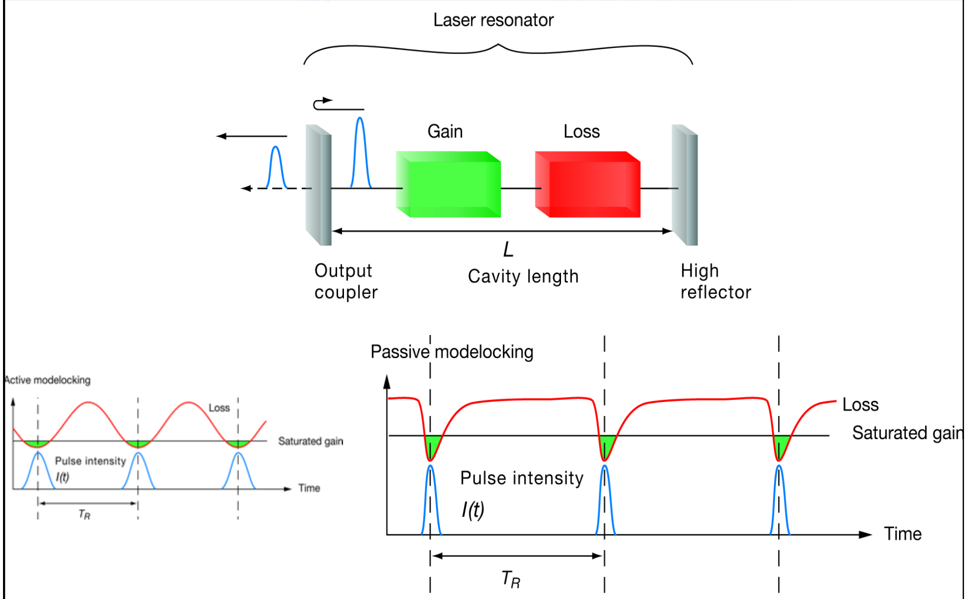
Outline

- Why and how was the SESAM invented?
- Challenge: need fast saturable absorber for shorter pulses
  Solution: Defect management (low temperature growth, AlAs traps, surface traps ...)
- Problem: Q-switching instabilities for passively modelocked solid-state lasers
  Solution: SESAM parameters
  (semiconductor saturable absorber material + mirror design freedom ideal)
- Challenge: SESAM damage
  Solution: Mode size and inverse saturable absorption
- Problem: Need fast saturable absorber for solid-state lasers (with no dynamic gain saturation)
  Solution: Soliton modelocking
- Problem: Pulses so short that position of electric field underneath pulse envelope needs to be stabilized
  Solution: Carrier envelope offset frequency (CEO) stabilization
  ... this solution also enabled the frequency metrology revolution
- Modelocking and frequency metrology: stabilized frequency combs
- Frontier lasers need different SESAM design parameters ... ongoing research.

Balance between loss modulation and gain



Passive Modelocking



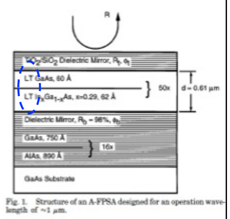
LT grown SESAMs to reduce absorber recovery time

February 1, 1993 / Vol. 18, No. 3 / OPTICS LETTERS 217

Self-starting and self-Q-switching dynamics of passively mode-locked Nd:YLF and Nd:YAG lasers

U. Keller, T. H. Chiu, and J. F. Ferguson

AT&T Bell Laboratories, Crawfords Corner Road, Holmdel, New Jersey 07733



Received August 12, 1992

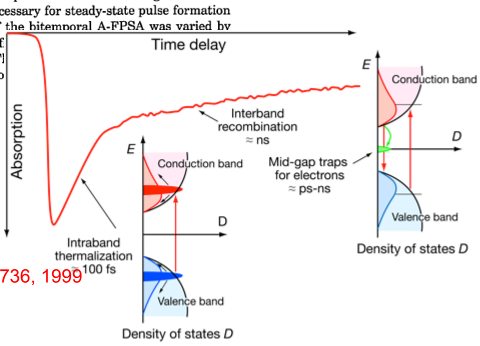
The semiconductor antiresonant Fabry–Perot saturable absorber (A-FPSA) has a bitemporal absorption response with a slow time component that is due to carrier recombination and a fast time component that is due to intraband thermalization. We demonstrate that the slow component provides the self-starting mechanism and without significant Kerr lens contribution the fast component is necessary for steady-state pulse formation in passively cw mode-locked solid-state lasers. The carrier lifetime of the bitemporal A-FPSA was varied by the molecular-beam-epitaxy growth temperature to characterize its inf switching dynamics of cw mode-locked Nd:YLF and Nd:YAG lasers. Tl reflector of the A-FPSA can be adjusted to optimize the self-starting perfo of cw mode-locked solid-state lasers.

Adjustable parameter: absorber recovery time

More on LT MBE growth and ion implantation to reduce recovery time of SESAMs:

Appl. Phys. Lett., vol. 74, 3134-3136, 1999
Appl. Phys. Lett., vol. 74, pp. 1269-1271, 1999
Physica B: Condensed Matter, vol. 273-274, pp. 733-736, 1999

Appl. Phys. Lett., vol. 75, pp. 1437-1439, 1999
Appl. Phys. Lett., vol. 74, pp. 1993-1995, 1999



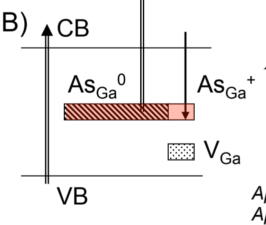
Low temperature MBE growth: LT GaAs

(a) LT GaAs: as grown

$As_{Ga}^{0} \rightarrow CB$ -transition strong (nonsaturable losses increased)

Conduction band (CB)

mid-gap defects: As antisites



As_{Ga}^{+} = electron traps

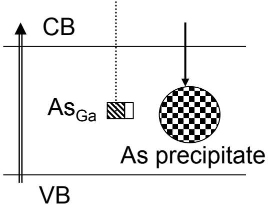
Valence band (VB)

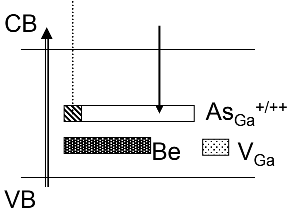
Appl. Phys. Lett. **74**, 3134, 1999
Appl. Phys. Lett. **74** 1269, 1999
Physica B: Condensed Matter **273-274**, 733,1999

(b) Undoped annealed

(c) Beryllium doped as grown

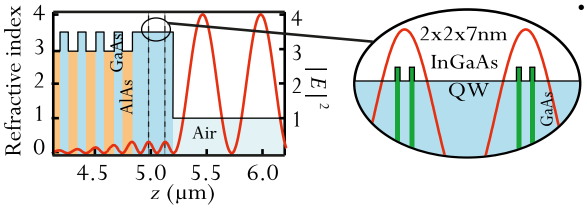
nonsaturable losses reduced





SESAM recovery time – more recent

SESAM design

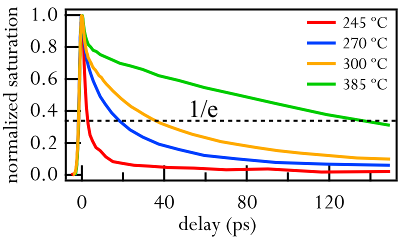


- DBR: 30-pair GaAs/AlAs
- Absorber section:
  - → antiresonant configuration
  - → 2x2-nm InGaAs quantum wells in two consecutive notes of electric field
  - → T_{growth} = 245°C, 270°C, 300°C, 385°C

Measured recovery

T_{growth} (°C)	**245**	**270**	**300**	**385**
F_{sat} (μJ/cm²)	32	31	25	34
ΔR (%)	3.9	3.6	4	3.6
ΔR_{ns} (%)	1.2	0.4	0.2	0.1
F_2 (mJ/cm²)	1460	1430	1230	1600
τ_{slow} (ps)	66	88	107	167
τ_{fast} (ps)	2	3	5	2
$\tau_{1/e}$ (ps)	3	17	33	128

$$R(\tau) = Ae^{-\frac{\tau}{\tau_{fast}}} + (1-A)e^{-\frac{\tau}{\tau_{slow}}}$$



Outline

- Why and how was the SESAM invented?
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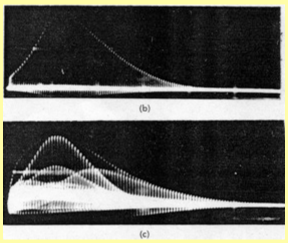
  ... this solution also enabled the frequency metrology revolution
- Modelocking and frequency metrology: stabilized frequency combs
- Frontier lasers need different SESAM design parameters ... ongoing research.

Ultrashort pulse generation with modelocking

A. J. De Maria, D. A. Stetser, H. Heynau
Appl. Phys. Lett. **8**, 174, 1966



200 ns/div

50 ns/div

Nd:glass
first passively modelocked laser
Q-switched modelocked

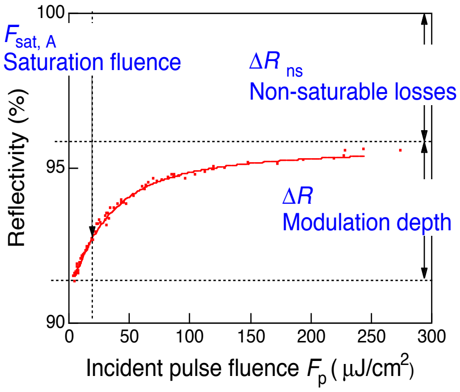
Q-switching problem in passively modelocked solid-state lasers:

- active modelocking for solid-state lasers
- dye lasers solved the problem

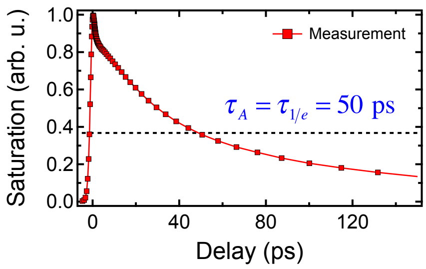
1960 1970 1980 1990 2000
Year

Flashlamp-pumped solid-state lasers

Basic SESAM Parameters



τ_A
Recovery time of absorber
typically $\tau_A = \tau_{1/e}$



Guidelines how to measure these parameters:
M. Haiml, R. Grange, U. Keller, *Appl. Phys. B* **79**, 331, 2004
with improved accuracy: D. J. H. Maas, et al., *Optics Express* **16**, 7571, 2008

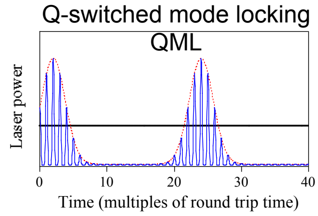
Recovery time: how short?
See later soliton modelocking and frontier lasers

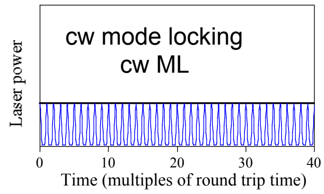
Q-switched mode locking is avoided if...

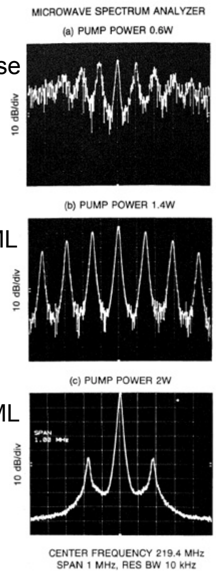
C. Hönninger, R. Paschotta, F. Morier-Genoud, M. Moser, and U. Keller, *JOSA B* ***16****, 46 (1999)*

$$E_P^2 > E_{sat,L} E_{sat,A} \Delta R = A_{eff,A} F_{sat,A} \Delta R$$

$$F_{sat,L} = \frac{h\nu}{\sigma}$$

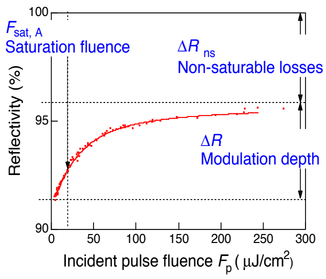






Appl. Phys. B **58**, 347, 1994

SESAMs to reduce Q-switching instabilities



$$E_P^2 > E_{sat,L} E_{sat,A} \Delta R = A_{eff,A} F_{sat,A} \Delta R$$

2005 Design guidelines
SESAMs with low saturation fluence $F_{sat,A}$

Appl. Phys. B 81, 27–32 (2005)
DOI: 10.1007/s00340-005-1879-1
Applied Physics B
Lasers and Optics

Semiconductor saturable absorber mirror structures with low saturation fluence

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K.J. WEINGARTEN[2]
R. GRANGE[1]
L. KRAINER[1]
M. HAIML[1]
V. LIVERINI[1]
M. GOLLING[1]
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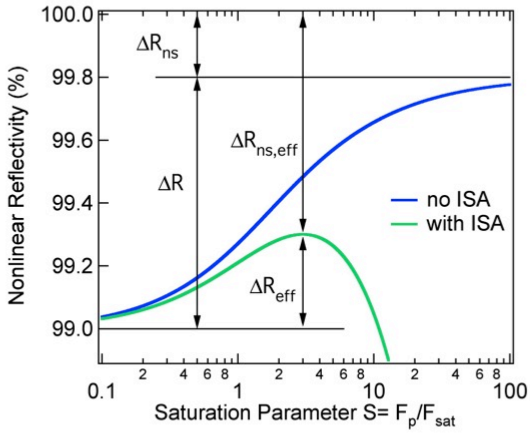
U. KELLER[1,✉]

[1] ETH Zurich, Physics Department, Institute of Quantum Electronics, Wolfgang-Pauli-Strasse 16, 8093 Zürich, Switzerland
[2] Time-Bandwidth Products, GigaTera Product Group, Technoparkstr. 1, 8005 Zürich, Switzerland

Inverse saturable absorption (ISA)

SESAM reflectivity for a pulse fluence F_p



the reflectivity decreases at higher pulse energies

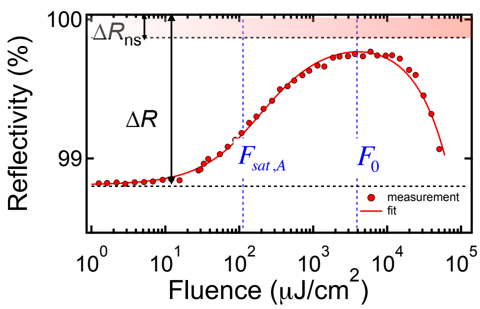
⬇

the roll-over = inverse saturable absorption

$$R_{ISA}(F_p) = R_P(F_p) - \frac{F_p}{F_2}$$

- F_2 is the inverse slope of the roll over
- The smaller F_2, the stronger is the roll-over
- Reason: Example TPA (Two Photon Absorption)

SESAMs to reduce Q-switching instabilities



F_0

Fluence on absorber at maximum reflectivity

$$F_0 \approx \sqrt{\Delta R \cdot F_{sat,A} \cdot F_2}$$

$$F_2 = \frac{\tau_p}{0.585 \int \beta_{TPA}(z) \cdot n^2 \cdot |E(z)|^4 \, dz}$$

2005 SESAMs with inverse saturable absorption (ISA):

Appl. Phys. B 80, 151–158 (2005)
DOI: 10.1007/s00340-004-1622-3
Applied Physics B
Lasers and Optics

New regime of inverse saturable absorption for self-stabilizing passively mode-locked lasers

R. GRANGE[1,✉]
M. HAIML[1]
R. PASCHOTTA[1]
G.J. SPÜHLER[1]
L. KRAINER[1]
M. GOLLING[1]
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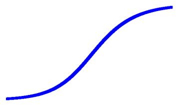
[1] Institute of Quantum Electronics, Physics Department, Swiss Federal Institute of Technology (ETH), ETH Zürich Hönggerberg, Wolfgang-Pauli-Str. 16, 8093 Zürich, Switzerland
[2] Avalon Photonics, Badenerstrasse 569, P.O. Box, 8048 Zürich, Switzerland
[3] FIRST Center for Micro- and Nanoscience, Swiss Federal Institute of Technology (ETH), ETH Zürich Hönggerberg, Wolfgang-Pauli-Str. 10, 8093 Zürich, Switzerland

Consequences for the QML Threshold

No inverse sat. absorption

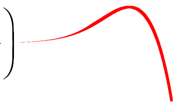
$$E_P > E_{sat,L} \frac{\Delta R}{S}$$



C. Hönninger, R. Paschotta, F. Morier-Genoud, M. Moser, and U. Keller
J. Opt. Soc. Am. B **16**, 46 (1999)

With inverse sat. absorption

$$E_P > E_{sat,L} \frac{\Delta R}{S}\left(1 - \frac{S^2}{S_0^{\,2}}\right)$$



R. Grange, M. Haiml, R. Paschotta, G. J. Spühler, L. Krainer, O. Ostinelli, M. Golling, U. Keller
Appl. Phys. B **80**, 151 (2005)

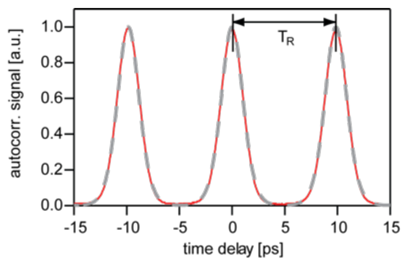
E_P	Intracavity pulse energy
$E_{sat,L}$	Gain saturation energy
$S = E_P/E_{sat,A}$	Saturation Parameter

$$S_0 = \sqrt{\frac{F_2 \Delta R}{F_{sat}}}$$ Saturation parameter at maximum reflectivity

- **Less demands on the mode size in the gain medium**
- **More flexibility for cavity design**
- **Easier to suppress Q-switched mode locking**

All-optical 100-GHz pulse generation at 1.5 µm

Autocorrelation



Optical spectrum

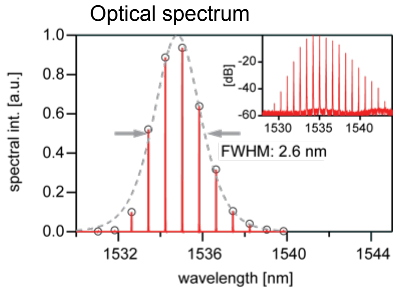
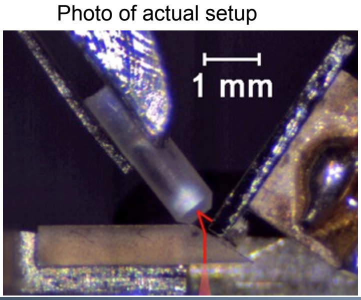


Photo of actual setup



SESAM modelocked Er-Yb:glass laser
Pulse repetition rate: 101 GHz
Max. output-power: 35 mW
Optical bandwidth: 2.6 nm
Pulse width: 1.6 ps (1.7x TBP)

A. E. H. Oehler et al., Opt. Express **16**, 21930, 2008

SESAM modelocked Er-Yb:glass (ERGO) laser enabled world-record optical communication results

Time-Bandwidth Products, Inc. made such lasers commercially available

ERGO laser, http://www.time-bandwidth.com

ARTICLES
PUBLISHED ONLINE: 22 MAY 2011 | DOI: 10.1038/NPHOTON.2011.74
nature photonics

26 Tbit s^{-1} line-rate super-channel transmission utilizing all-optical fast Fourier transform processing

D. Hillerkuss[1]*, R. Schmogrow[1], T. Schellinger[1], M. Jordan[1], M. Winter[1], G. Huber[1], T. Vallaitis[1], R. Bonk[1], P. Kleinow[1], F. Frey[1], M. Roeger[1], S. Koenig[1], A. Ludwig[1], A. Marculescu[1], J. Li[1], M. Hoh[1], M. Dreschmann[1], J. Meyer[1], S. Ben Ezra[2], N. Narkiss[2], B. Nebendahl[3], F. Parmigiani[4], P. Petropoulos[4], B. Resan[5], A. Oehler[5], K. Weingarten[5], T. Ellermeyer[6], J. Lutz[6], M. Moeller[7], M. Huebner[1], J. Becker[1], C. Koos[1], W. Freude[1]* and J. Leuthold[1]*

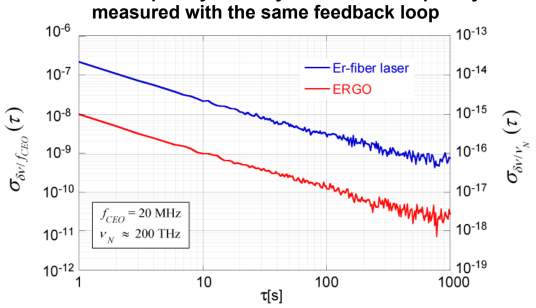
... and also enables low-noise frequency combs

DPSSLs (Diode-Pumped Solid-State Lasers)
+ high-Q cavity, low nonlinearities
  ⇒ extremely low intrinsic noise
+ convenient and robust

Example excellent noise performance of DPSSLs: Optical ultra-stable microwave oscillator

Compare | 75 MHz 1.5-µm Er:Yb glass DPSSL | with | commercial 1.5-µm Er-fiber laser |

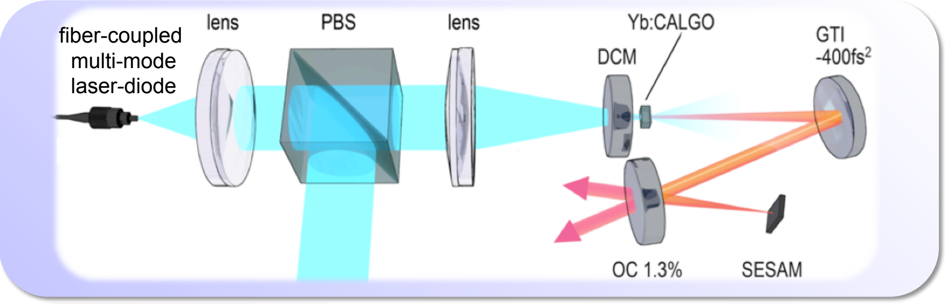
Relative frequency stability of the CEO frequency measured with the same feedback loop



S.Schilt, N. Bucalovic, V. Dolgovskiy, C. Schori, M. C. Stumpf, G. Di Domenico, S. Pekarek, A. E. H. Oehler, T. Südmeyer, U. Keller, P. Thomann, "Fully stabilized optical frequency comb with sub-radian CEO phase noise from a SESAM-modelocked 1.5-µm solid-state laser" *Optics Express* **19**, 24171, 2011

(right scale: relative frequency stability with respect to the optical carrier)

1.8-GHz femtosecond Yb:CALGO laser

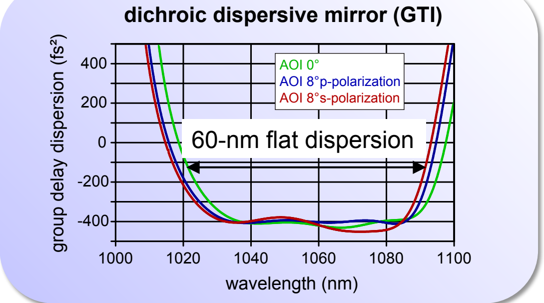


SESAM* **(grown at ETH)**

Structure	AlAs-embedded QW
F_{sat}	11.3 µJ/cm²
ΔR	1.36%
ΔR_{ns}	<0.3%
F_2	275 mJ/cm²

*Measured at 80 fs, 1051 nm, 20 °C

dichroic dispersive mirror (GTI)



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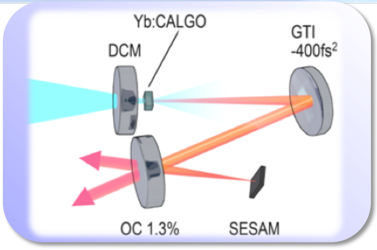

f_{rep} = 1.8 GHz τ_p = 59.4 fs

P_{av} = 3.0 W P_{pk} = 24.3 kW

λ_0 = 1059.7 nm

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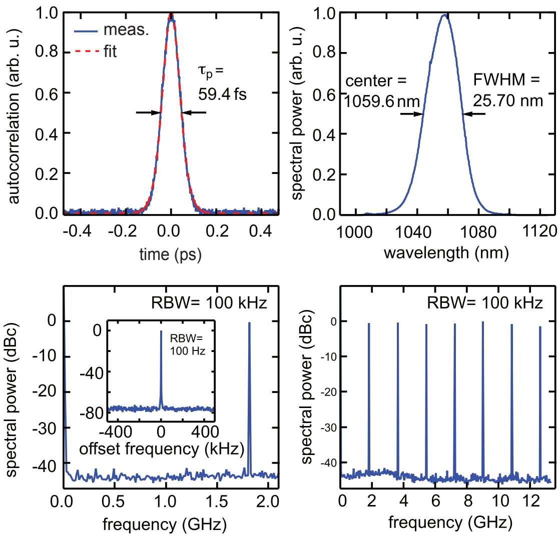
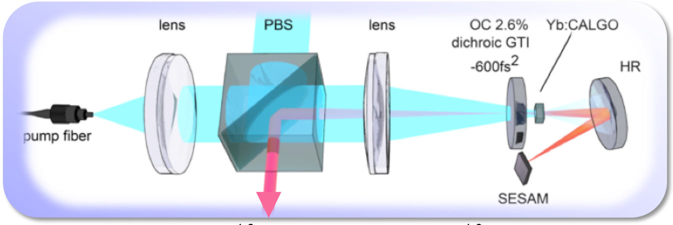


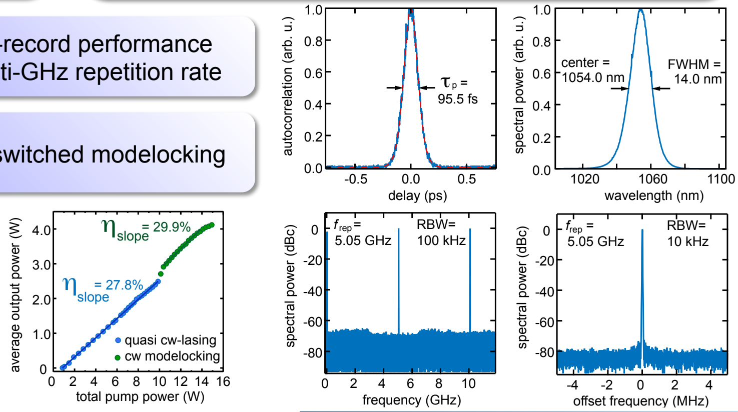
A. Klenner et al., Opt. Express **22**, no. 9, pp. 11884-11891, 2014

High-power 5-GHz solid-state laser

f_{rep} = 5.1 GHz
P_{av} = 4.1 W
t_P = 95.5 fs
P_{pk} = 7.5 kW



- world-record performance at multi-GHz repetition rate
- no Q-switched modelocking



A. Klenner, U. Keller, *Optics Express* 23, 8532 (2015)

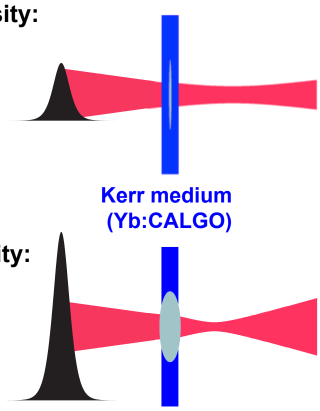
Q-switching limiter: design

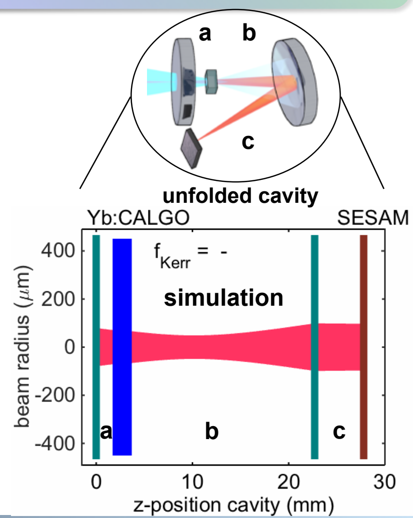
QML:
- **peak intensities increase**
- **Kerr lens increases**

laser design idea:
- **Kerr lens increases SESAM mode size**
- **induces a limiter to prevent QML**

moderate peak intensity:

high peak intensity:





A. Klenner, U. Keller, *Optics Express* **23**, 8532 (2015)

Outline

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- Frontier lasers need different SESAM design parameters ... ongoing research.

SESAM without damage (even at >100 kW)

2012

IEEE JOURNAL OF SELECTED TOPICS IN QUANTUM ELECTRONICS, VOL. 18, NO. 1, JANUARY/FEBRUARY 2012 29

SESAMs for High-Power Oscillators: Design Guidelines and Damage Thresholds

Clara J. Saraceno, Cinia Schriber, Mario Mangold, Martin Hoffmann, Oliver H. Heckl, Cyrill R. E. Baer, Matthias Golling, Thomas Südmeyer, and Ursula Keller

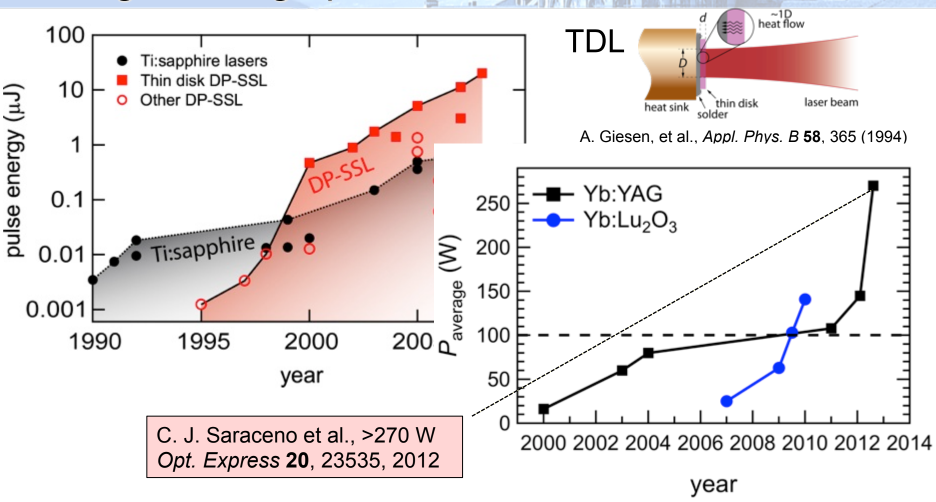
(Invited Paper)

***Abstract*—We present for the first time to the best of our knowledge a systematic study of lifetime and damage of semiconductor saturable absorber mirrors (SESAMs) designed for operation in high-power oscillators. We characterize and compare nonlinear reflectivity and inverse saturable absorption (ISA) parameters as well as damage threshold and lifetime of different representative SESAMs under test using a nonlinear reflectivity measurement setup at unprecedented high fluence levels. We investigate the catastrophic damage that occurs at very high fluences by demonstrating a dependence of the damage threshold on the ISA parameter F_2 and the maximum reflectivity fluence F_0. We can clearly demonstrate that the damage fluence F_d scales proportionally to $\sqrt{F_2}$ for all SESAMs. In the case of SESAMs with the same absorber where the product $F_{sat} \cdot \Delta R$ is constant, the damage fluence F_d scales proportionally to F_0. Therefore, damage occurs due to heating of the lattice by the energy absorbed due to the ISA process and is not related to the quantum well (QW) absorbers. Furthermore, we present guidelines on how to design samples with high saturation fluences, reduced induced absorption, and high damage thresholds. Using multiple QWs and a suitable dielectric topsection, we achieved SESAMs with saturation fluences $>200\ \mu J/cm^2$, nonsaturable losses $<0.1\%$, and reduced ISA. Our best sample could not be damaged at a maximum available fluence of $0.21\ J/cm^2$ and a peak intensity of $370\ GW/cm^2$. These SESAMs will be suitable for future high-power femtosecond oscillators in the kilowatt average output power regime, which is very interesting for attosecond science and industrial material processing applications.**

various fields, such as physics, chemistry, biology, materials science, imaging, material processing, communication, and medicine. The invention of the semiconductor saturable absorber mirror (SESAM) [3], [4] nearly 20 years ago was a major advancement for the development of simple and reliable ultrafast laser systems. It enabled the first stable and self-starting passive modelocking of diode-pumped solid-state lasers (DPSSLs), resolving the long-standing Q-switching problem [5]. Today, SESAMs have become key devices for modelocking of numerous laser types, including DPSSLs, fiber lasers, and semiconductor lasers. Semiconductors are ideally suited as saturable absorbers because they can cover a broad wavelength range and yield short recovery times, supporting the generation of picosecond to femtosecond pulse durations. The macroscopic nonlinear optical parameters for modelocking can be optimized over a wide range by the design of the mirror structure and the choice of the semiconductor absorber.

SESAM modelocking is currently the best-suited technology for high-power ultrafast laser oscillators. Recent SESAM modelocked thin-disk lasers have achieved average powers >140 W [6] and pulse energies >25 μJ [7], which are higher than for any other ultrafast oscillator technology. The combination of high power levels and multimegahertz repetition rates makes these lasers highly attractive for areas such as high-field

High average power lasers: SESAM ML TDL



A. Giesen, et al., *Appl. Phys. B* **58**, 365 (1994)

C. J. Saraceno et al., >270 W
Opt. Express **20**, 23535, 2012

First time >10 µJ pulse energy from a SESAM modelocked Yb:YAG thin disk laser (TDL)
Opt. Express **16**, 6397, 2008 and CLEO Europe June 2007

26 µJ with a multipass gain cavity and larger output coupling of 70% (Trumpf/Konstanz)
Opt. Express **16**, 20530, 2008

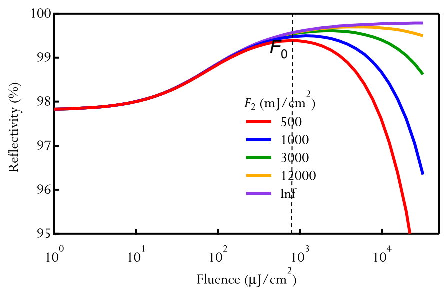
Tested SESAMs with different rollover

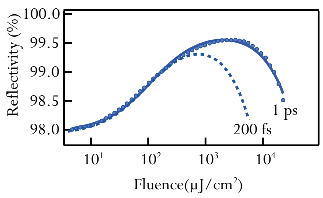
Rollover: influence of two-photon absorption (TPA)

$$F_2 = \frac{\tau_p}{0.585 \int \beta_{TPA}(z)\, n^2(z)\, |\varepsilon(z)|^4\, dz}$$ and $F_0 \approx \sqrt{\Delta R F_{sat} F_2}$ (for weak TPA)

SESAM	F_0 (mJ/cm²)	$S_0 = F_0/F_{sat}$	$F_{2,meas}$ (mJ/cm²)	$F_{2,calc}$ (mJ/cm²)	$F_{2,calc}/F_{2,meas}$
NTC	3.1	43	3200	8200	2.56
SCTC	3.3	12	5523	15000	2.71
DTC2	8.7	52	31700	70200	2.21
DTC3	30.2	122	346000	206000	0.6

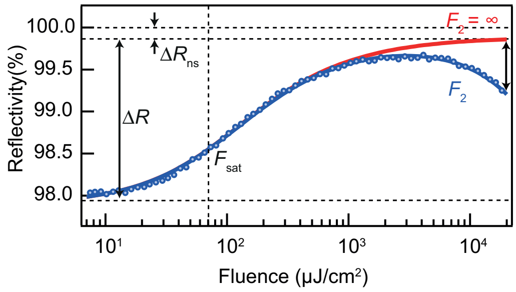
- Topcoating increases F_2
- Rollover stronger than TPA only: ratio confirms previous study





C. J. Saraceno et al, *IEEE J. Selected Topics in Quantum Electronics (JSTQE)* **18**, 29-41, 2012

Damage of SESAM



Rollover: deposited energy

$$F_{abs} = F(1 - R(F))$$

$$R(F) = R_{ns}\frac{\ln\left(1 + (R_{lin}/R_{ns})(e^{F/F_{sat}} - 1)\right)}{F/F_{sat}} e^{-\frac{F}{F_2}} \approx R_{ns}\left(1 - \frac{F}{F_2}\right)$$

$$F_{abs} \approx R_{ns}\frac{F^2}{F_2} \rightarrow F_d \propto \sqrt{F_2}$$

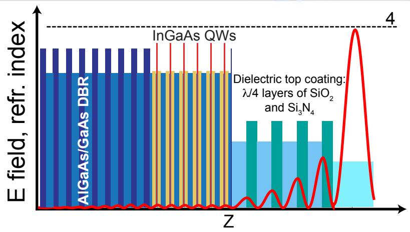
Damage occurs at a constant amount of deposited energy

Simple guidelines

- ✓ small modulation depths ($\Delta R_{ns} << \Delta R$)
- ✓ small nonsaturable losses
- ✓ $F >> F_{sat}$
- ✓ $F << F_2$

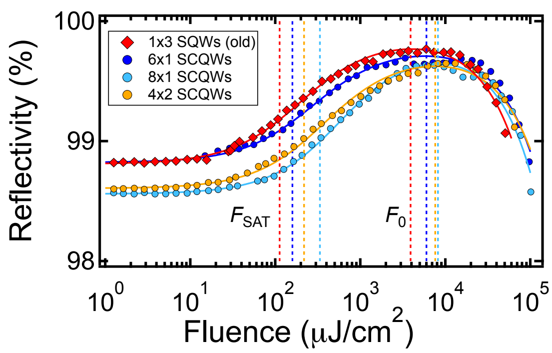
C. J. Saraceno et al, *IEEE J. Selected Topics in Quantum Electronics (JSTQE)* **18**, 29-41, 2012

Increased saturation parameters



- **MOVPE grown**
- 27-pair GaAs/$Al_{98}Ga_2As$ DBR
- **6-8 InGaAs QW** absorber layers, embedded in AlAs
- **$Al_{98}Ga_2As_{84}P_{16}$ strain compensation**
- **Four layer-pairs of SiO_2/Si_3N_4** (PECVD)

	MBE 3QWs	**MOVPE 8QWs**
F_{SAT}	≈ 120 µJ/cm²	**>300 µJ/cm²**
F_0	≈ 4 mJ/cm²	**>8 mJ/cm²**
F_2	≈ 6 J/cm²	**≈10 J/cm²**
ΔR	≈ 1.1 %	≈ 1.3 %
ΔR_{NS}	< 0.2 %	< 0.2%



Enhanced damage threshold

	MBE 3QWs	MOVPE 8QWs
F_{SAT}	≈ 120 µJ/cm²	**>300 µJ/cm²**
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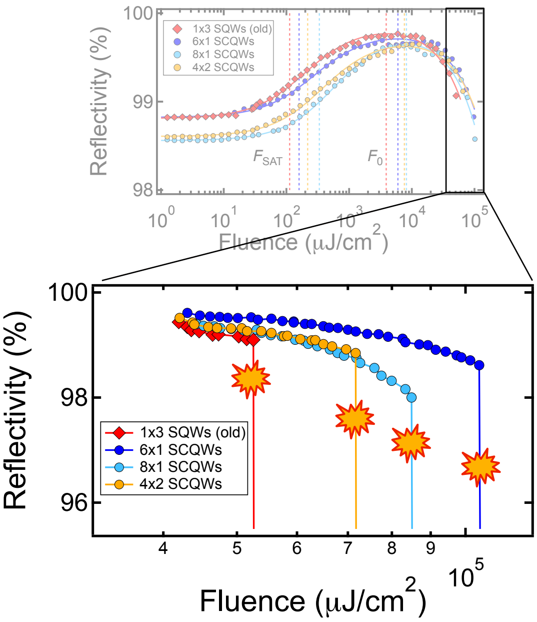
ΔR	≈ 1.1 %	≈ 1.3 %
ΔR_{NS}	< 0.2 %	< 0.2%

Novel SESAMs show unprecedented damage thresholds

- 1x3 SQWs → $F_D \approx 52$ mJ/cm²
- **6x1 SQWs → $F_D \approx 104$ mJ/cm²**
- 8x1 SQWs → $F_D \approx 85$ mJ/cm²
- 1x3 SQWs → $F_D \approx 72$ mJ/cm²



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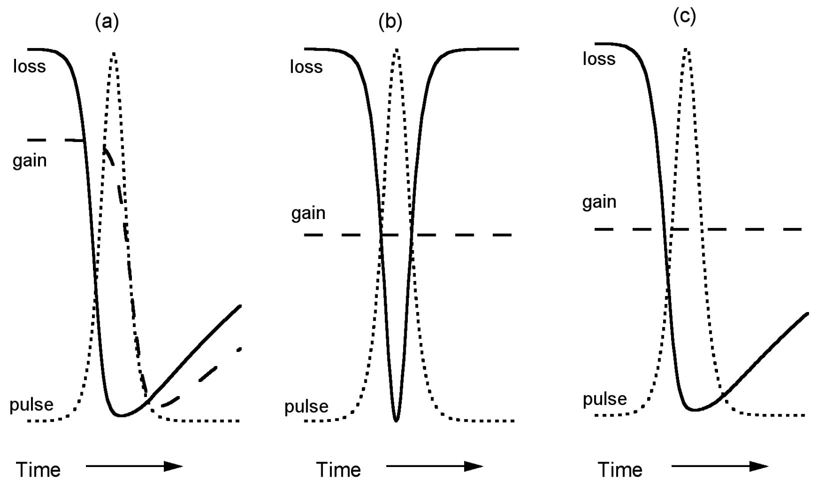
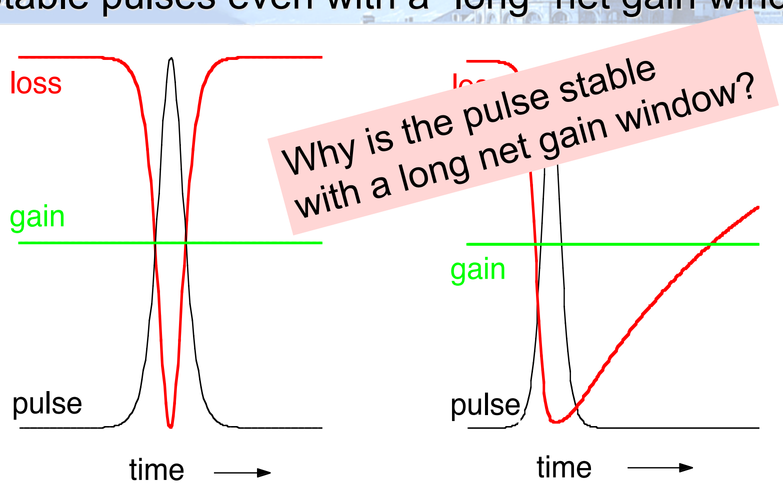
Pulse-shaping in passive modelocking



U. Keller, Ultrafast solid-state lasers, Landolt-Börnstein, Group VIII/1B1, edited by G. Herziger, H. Weber, R. Prop
pp. 33-167, 2007, ISBN 978-3-540-26033-2

Stable pulses even with a "long" net gain window



Kerr lens modelocking (KLM)

Fast saturable absorber

D. E. Spence, P. N. Kean, W. Sibbett
Opt. Lett. **16**, 42, 1991

Soliton modelocking

"not so fast" saturable absorber

F. X. Kärtner, U. Keller,
Opt. Lett. **20**, 16, 1995

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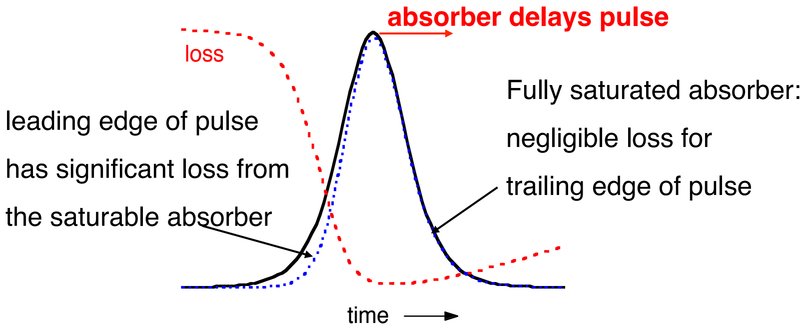
R. Paschotta, U. Keller, *Appl. Phys. B* **73**, 653, 2001



Dominant stabilization process with a relatively long net-gain window:

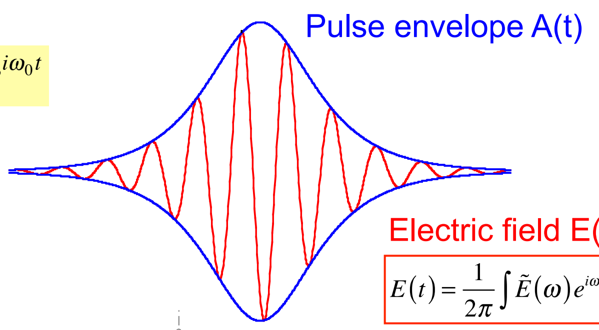
Picosecond domain: absorber delays pulse

The pulse is constantly moving backward and can swallow any noise growing behind itself.

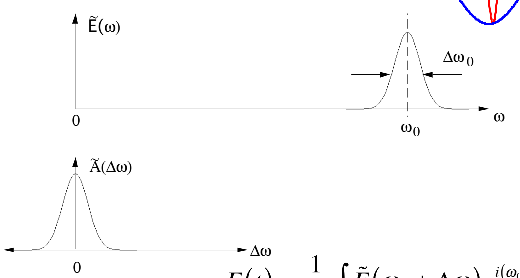
Femtosecond domain: dispersion in soliton modelocking

Laser pulse with pulse envelope

$$E(t) = A(t)e^{i\omega_0 t}$$



$$E(t) = \frac{1}{2\pi}\int \tilde{E}(\omega)e^{i\omega t}d\omega$$



$$\tilde{A}(\Delta\omega) = \tilde{E}(\omega_0 + \Delta\omega)$$

$$E(t) = \frac{1}{2\pi}\int \tilde{E}(\omega_0 + \Delta\omega)e^{i(\omega_0+\Delta\omega)t}d\Delta\omega = \frac{1}{2\pi}e^{i\omega_0 t}\int \tilde{A}(\Delta\omega)e^{i\Delta\omega t}d\Delta\omega$$

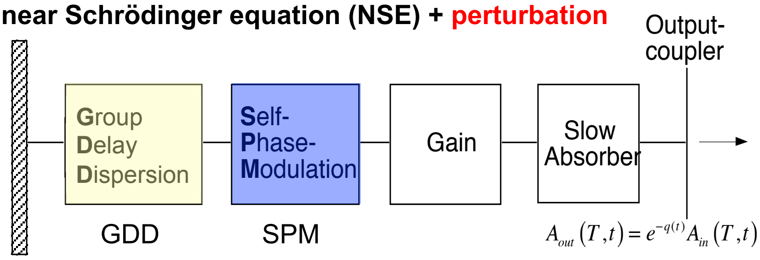
Online Video: Master Class 2014

More details on ultrafast pulse generation

http://www.ulp.ethz.ch/videos/physics-at-fom-2014-master-class.html

Soliton modelocking: GDD negative, $n_2 > 0$

Nonlinear Schrödinger equation (NSE) + perturbation



$$A_{out}(T,t) = e^{-q(t)} A_{in}(T,t)$$

$$A_{out}(T,t) = \left[1 - q(t)\right] A_{in}(T,t)$$

$$\Rightarrow \Delta A(T,t) = -q(t) A(T,t)$$

Master equation:
Opt. Lett 20, 16, 1995 and IEEE JSTQE 2, 540, 1996

$$T_R \frac{\partial}{\partial T} A(T,t) = \left(iD \frac{\partial^2}{\partial t^2} - i\delta \left| A(T,t) \right|^2 \right) A(T,t) + \left(g - l + D_g \frac{\partial^2}{\partial t^2} - q(t) \right) A(T,t) = 0$$

$$A(T,t) = \left(A_0 \operatorname{sech}\left(\frac{t}{\tau}\right) \right) \exp\left[i\phi_0 \frac{T}{T_R} \right] + \text{continuum}$$

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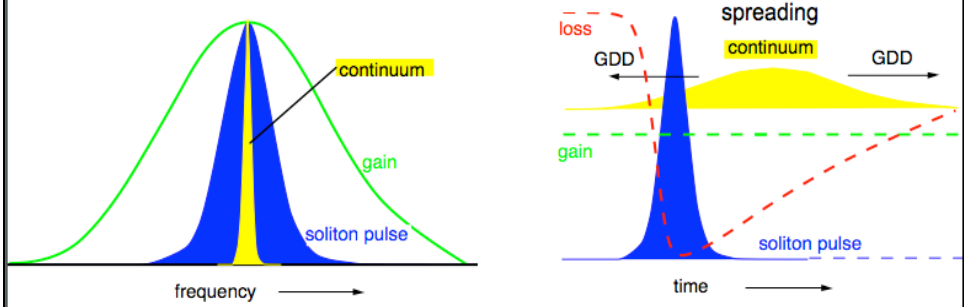
Invited Paper: F. X. Kärtner, I. D. Jung, U. Keller, IEEE JSTQE, 2, 540, 1996

Soliton Perturbation Theory:

$$A(T,t) = \underbrace{\left(A\,\mathrm{sech}\left(\frac{t}{\tau}\right)\right) \exp\left[i\Phi_0 \frac{T}{T_R}\right]}_{\text{soliton}} + \underbrace{\textbf{\textit{small perturbations}}}_{\text{"continuum"}}$$

"continuum" only GDD & SAM (no SPM)



Stabilization: Dispersion spreads continuum out where it sees more loss

Experimental confirmation: Ti:sapphire laser

Solution: soliton pulse $A_s(T,t) = \sqrt{\frac{F_{p,L}}{2\tau}}\,\mathrm{sech}\left(\frac{t}{\tau}\right) e^{i\phi_0 \frac{T}{T_R}}$

soliton phase per resonator roundtrip

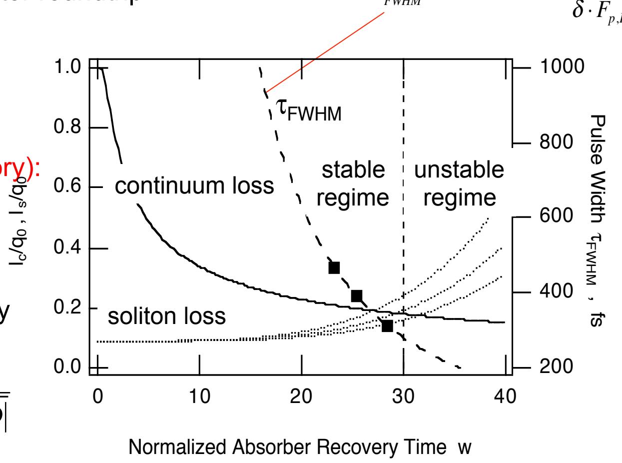
$$\phi_0 = \frac{|D|}{\tau^2} = \frac{\delta \cdot F_{p,L}}{4\tau}$$

$$\tau_{FWHM} = 1.76 \cdot \tau = 1.76 \frac{4|D|}{\delta \cdot F_{p,L}}$$

Stability (soliton perturbation theory): continuum loss l_c is larger than soliton loss l_s

Normalized abs. recovery

$$w = \frac{\tau_A}{\tau}\sqrt{\frac{q_0}{\phi_0}} = \tau_A \sqrt{\frac{q_0}{|D|}} \propto \frac{1}{\sqrt{|D|}}$$



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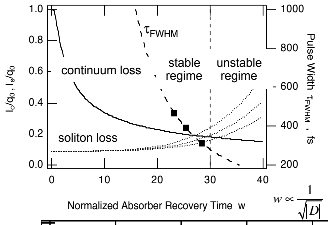

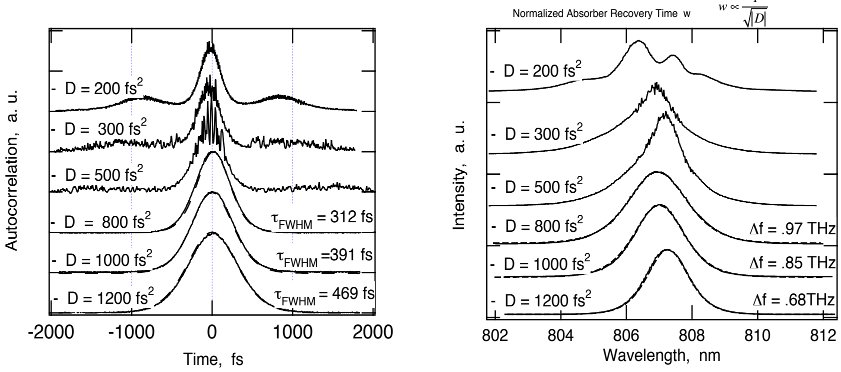

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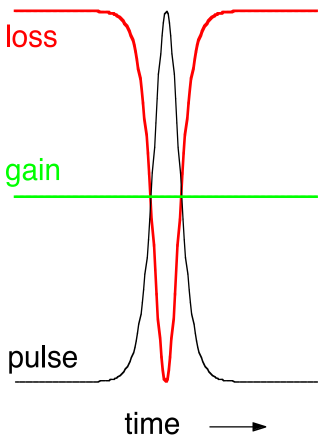

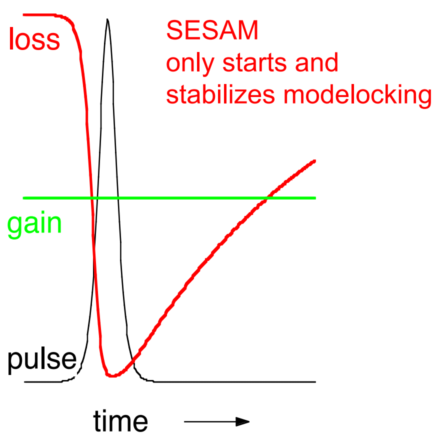

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ETH zürich

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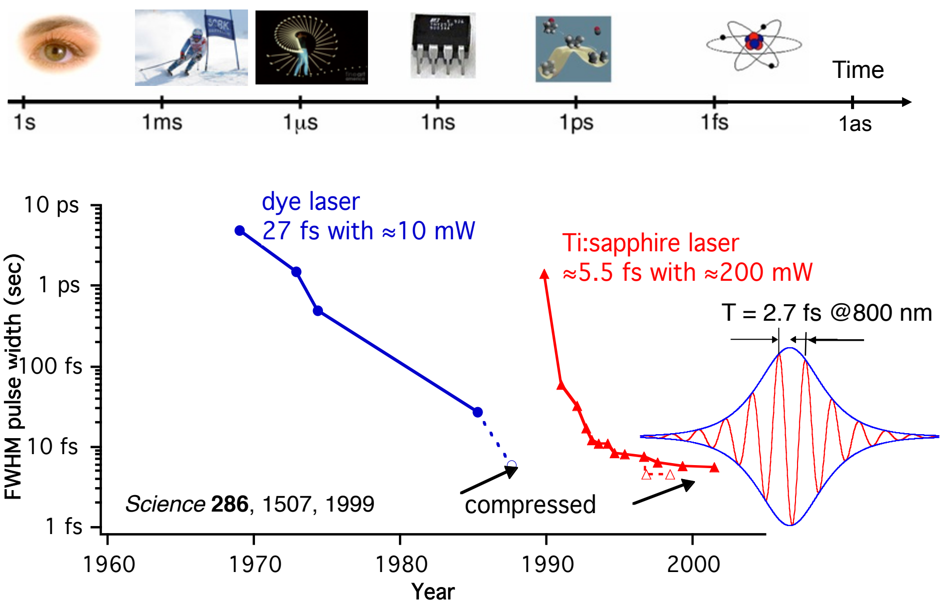
ETH zürich

Ultrashort pulse generation



How can we stabilize the frequency comb ?

1999

Appl. Phys. B 69, 327–332 (1999) / Digital Object Identifier (DOI) 10.1007/s003409900148

Applied Physics B
Lasers
and Optics

Carrier-envelope offset phase control: A novel concept for absolute optical frequency measurement and ultrashort pulse generation

H.R. Telle[1], G. Steinmeyer[2], A.E. Dunlop[2], J. Stenger[1], D.H. Sutter[2], U. Keller[2]

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Received: 19 August 1999/Published online: 8 September 1999

Abstract. The shortest pulses periodically emitted directly from a mode-locked Ti:sapphire laser are approaching the two-optical-cycle range. In this region, the phase of the optical carrier with respect to the pulse envelope becomes important in nonlinear optical processes such as high-harmonic generation. Because there are no locking mechanisms between envelope and carrier inside a laser, their relative phase offset experiences random fluctuations. Here, we propose several novel methods to measure and to stabilize this carrier-envelope offset (CEO) phase with sub-femtosecond uncertainty. The stabilization methods are an important prerequisite for attosecond pulse generation schemes. Short and highly periodic pulses of a two-cycle laser correspond to

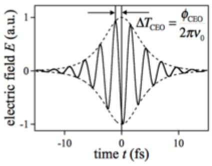
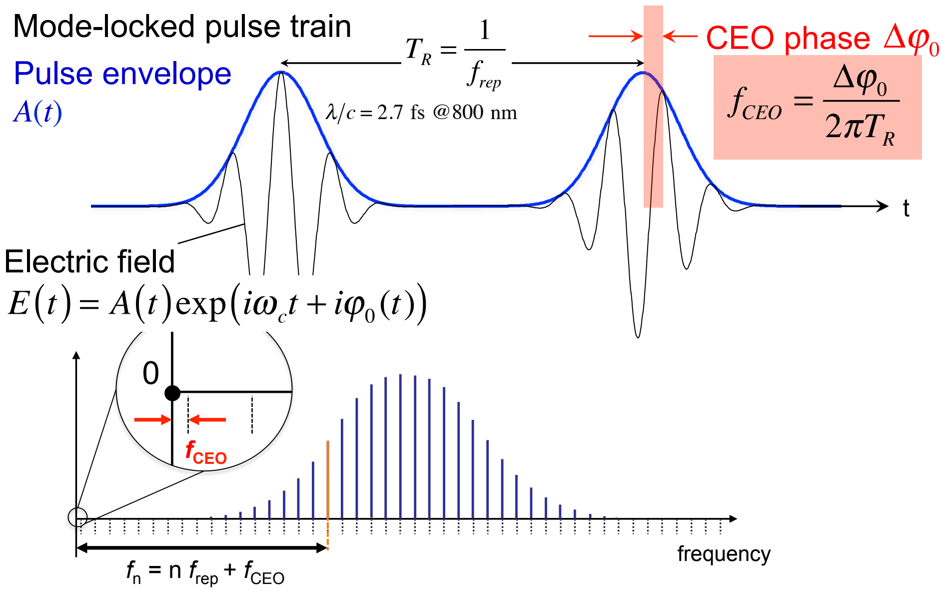


Fig. 1. 5-fs pulse with sech-shaped field envelope. The pulse-to-pulse carrier-envelope offset phase, ϕ_{CEO}, is proportional to the roundtrip delay of the central fringe, ΔT_{CEO}, and the carrier frequency, ν_0. ϕ_{CEO} is defined as the phase angle at pulse center

Carrier Envelope Offset (CEO)

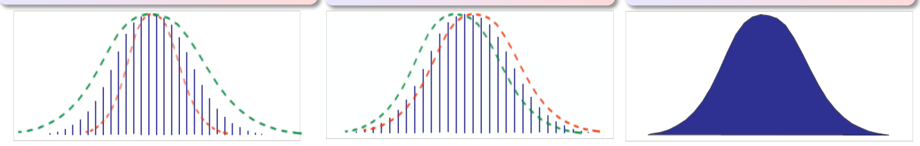


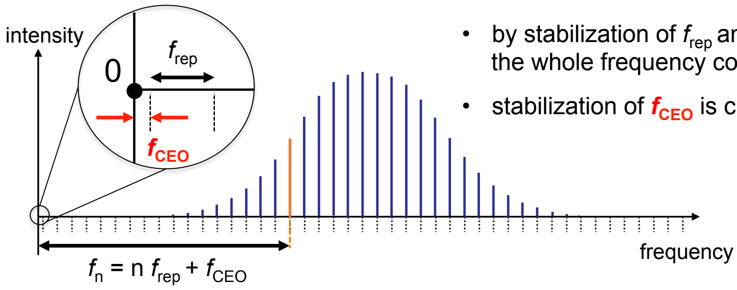
H.R. Telle, G. Steinmeyer, A.E. Dunlop, J. Stenger, D.H. Sutter and U. Keller, Appl. Phys. B 69, 327 (1999)

Frequency combs from modelocked lasers

free-running passively modelocked laser

unlocked repetition rate: f_{rep} | unlocked CEO: f_{CEO} | time average





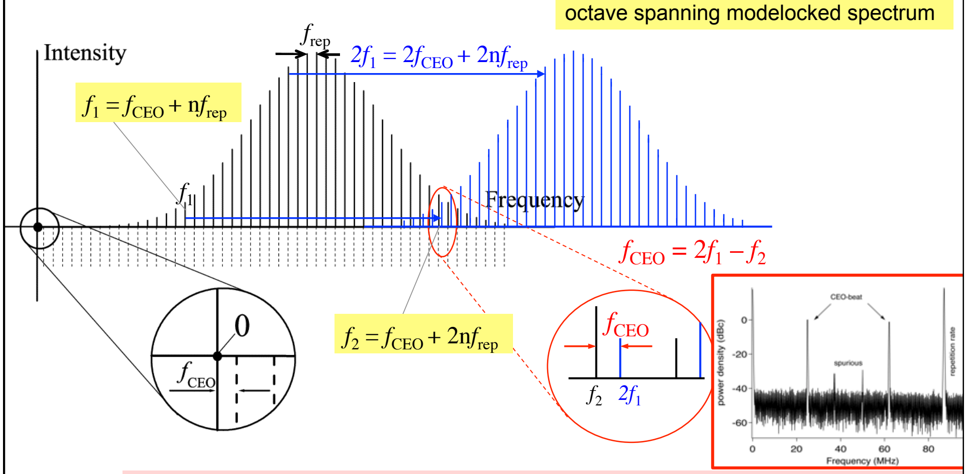
- by stabilization of f_{rep} and f_{CEO}, the whole frequency comb is locked!
- stabilization of f_{CEO} is challenging [1]

[1] comb self-referencing: H.R. Telle, G. Steinmeyer, A.E. Dunlop, J. Stenger, D.H. Sutter and U. Keller, Appl. Phys. B 69, 327 (1999)

How can we measure the frequency comb offset ?

f_{rep} : pulse repetition rate frequency , f_{CEO} : carrier envelope offset frequency

octave spanning modelocked spectrum

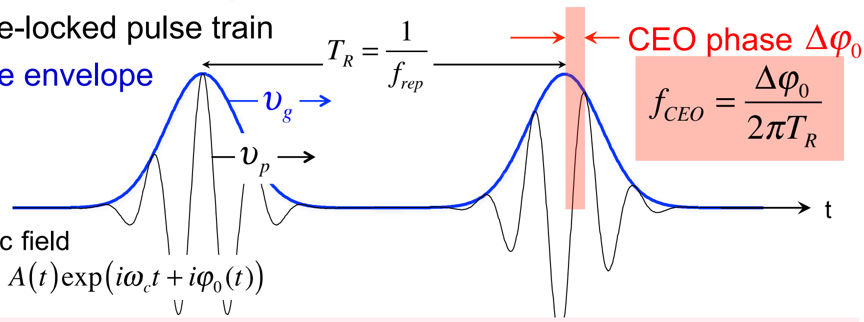


Mode beating of fundamental and second harmonic frequency comb
f-to-$2f$ interference technique: $f_{CEO} = 2f_1 - f_2$

H.R. Telle, G. Steinmeyer, A.E. Dunlop, J. Stenger, D.H. Sutter and U. Keller, Appl. Phys. B 69, 327 (1999)

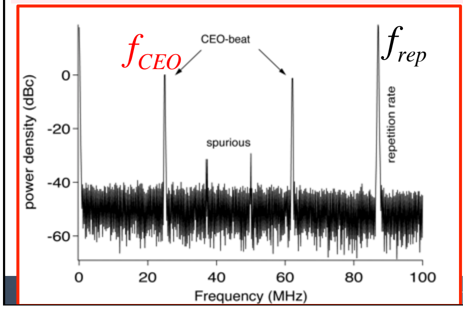
How can we stabilize the frequency comb offset ?

Mode-locked pulse train



Electric field
$E(t) = A(t)\exp(i\omega_c t + i\varphi_0(t))$

Mode beating measured with a simple photodetector and observed on an microwave spectrum analyzer

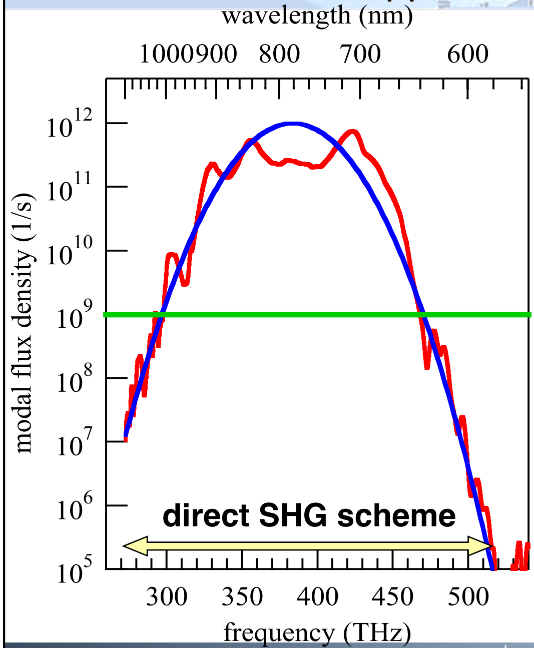


Anything where

$$\Delta\upsilon_p \neq \Delta\upsilon_g$$

inside the modelocked laser

World-record Ti:sapphire laser spectrum in 1999



Schemes and feasibilty test to measure and stabilize carrier envelope offset (CEO)

H. R. Telle et al.
Appl. Phys. B 69, 327, 1999

detection limit required to avoid cycle slips

Octave spanning spectrum required for *f-2f* self-referencing technique (initially called direct SHG scheme)

How can we stabilize the frequency comb ?

$$\nu(m) = \nu_{CEO} + m\, f_{rep}$$

1.1 Direct SHG (*f*-2*f* self-referencing technique)

$$2\nu(m) - \nu(2m) = \left(2\nu_{CEO} + 2m\, f_{rep}\right) - \left(\nu_{CEO} + 2m\, f_{rep}\right) = \nu_{CEO} \qquad (4)$$

one nonlinear optical process
needs octave spanning modelocked spectrum

1.2 Frequency doubled transfer oscillator

two nonlinear optical processes + one additional cw oscillator
but needs less modelocked spectrum

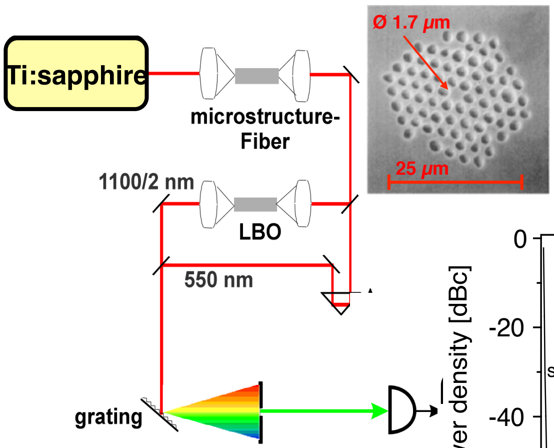
$\nu_{trans} = n\, f_{rep} \Rightarrow$ use feedback loop to stabillize transfer oscillator ν_{trans}

$$\nu(2n) - 2\nu_{trans} = \left(\nu_{CEO} + 2n\, f_{rep}\right) - 2n\, f_{rep} = \nu_{CEO} \qquad (5)$$

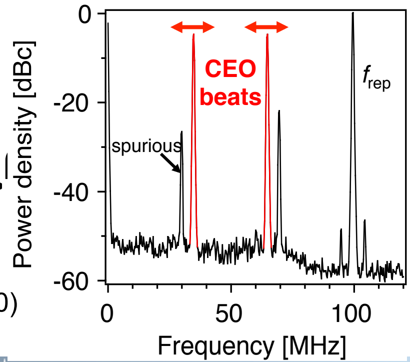
More techniques proposed to further reduce required bandwidth

CEO beat signal with external SCG

1.1 Direct SHG (*f*-to-2*f* interference technique) with SCG



Super continuum generation (SCG) in micro structure fiber:
J. Ranka et al., OL **25**, 25 (2000)



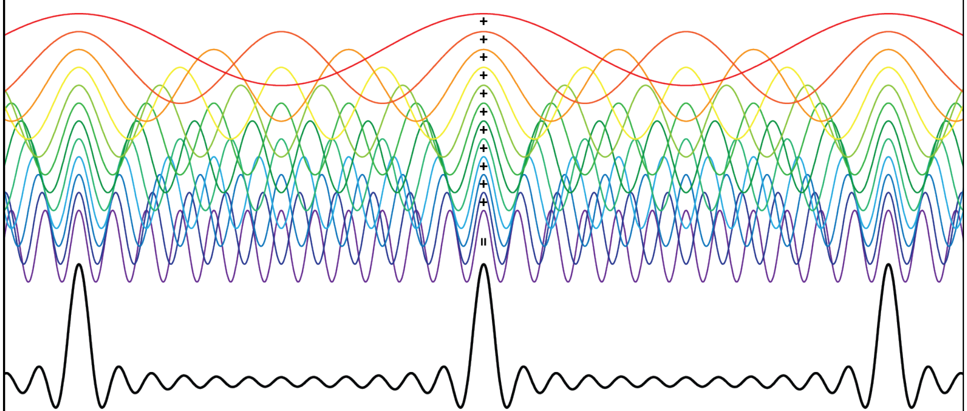
Hänsch and Hall group:
D.J. Jones et al., Science 288, 635 (2000)
A. Apolonski et al., PRL 85, 740 (2000)

Outline

- Why and how was the SESAM invented?
- Challenge: need fast saturable absorber for shorter pulses
  Solution: Defect management (low temperature growth, AlAs traps, surface traps ...)
- Problem: Q-switching instabilities for passively modelocked solid-state lasers
  Solution: SESAM parameters
  (semiconductor saturable absorber material + mirror design freedom ideal)
- Challenge: SESAM damage
  Solution: Mode size and inverse saturable absorption
- Problem: Need fast saturable absorber for solid-state lasers (with no dynamic gain saturation)
  Solution: Soliton modelocking
- Problem: Pulses so short that position of electric field underneath pulse envelope needs to be stabilized
  Solution: Carrier envelope offset frequency (CEO) stabilization
  ... this solution also enabled the frequency metrology revolution
- Modelocking and frequency metrology: stabilized frequency combs
- Frontier lasers need different SESAM design parameters ... ongoing research.

Laser pulse as a superposition of many frequencies

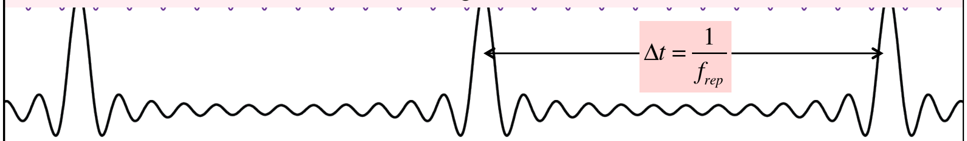
- A continuous wave laser emits in one or only few frequencies
- Typical femtosecond laser pulse trains are generated with a superposition of millions of single frequencies (1 femtosecond = 10^{-15} s)
- Single frequencies are phase locked with intracavity modulator (or saturable absorber): “modelocking”



Modelocked laser can give a „frequency ruler“

- Spectrum of a fs modelocked laser consists of millions of fine lines
- Line spacing is given by pulse repetition frequency f_{rep}:

Line spacing was stabilized in the 1980’s:
referred to as “timing jitter stabilization”
Patent D. Cotter (1985, British Telecom)
Actively modelocked flashlamp-pumped Nd:YAG laser (1986)
M. J. W. Rodwell, D. M. Bloom, K. J. Weingarten, *IEEE J. Quantum Electr.* **25**, 817, 1989



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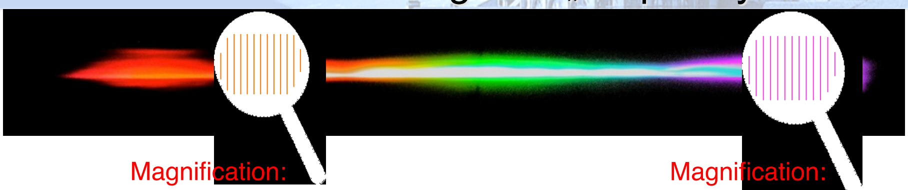

- Spectrum of a fs modelocked laser consists of millions of fine lines
- Line spacing is given by pulse repetition frequency f_{rep} and can be stabilized
- Femtosecond laser is for frequency the same as a ruler for length:

- **.... but the „zero“ of the frequency ruler was not stabilized!**

Solution given how to stabilize the zero of the frequency ruler:
H.R. Telle, G. Steinmeyer, A. E. Dunlop, J. Stenger, D. H. Sutter, U. Keller
Appl. Phys. B **69**, 327 (1999)

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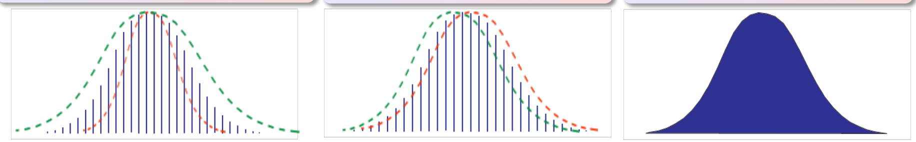

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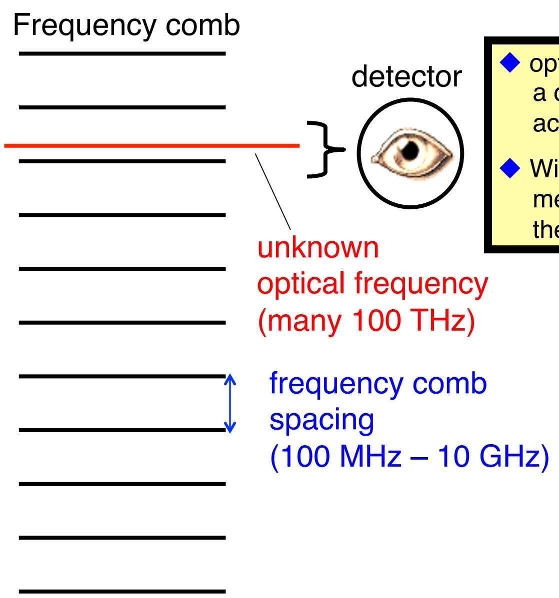
How can you measure optical frequencies?

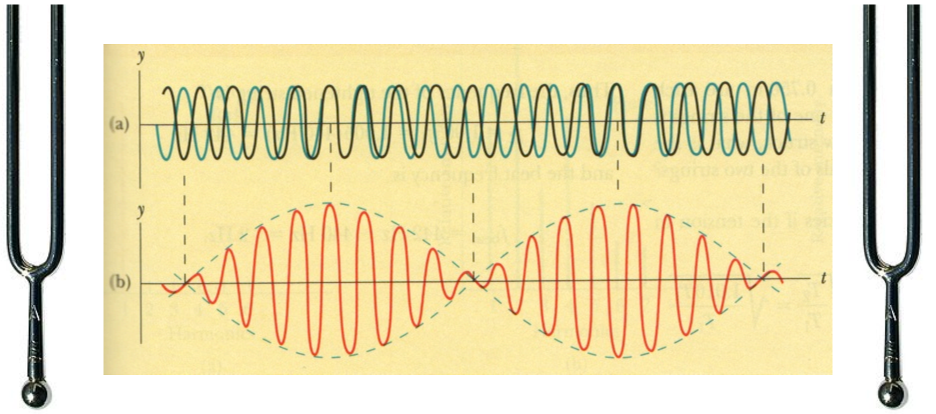


- optical frequencies too high for a direct measurement with high accuracy
- With frequency comb: measure unknown frequency with the beat signal on the detector

Tuning fork Nr. 1 at the frequency f_1

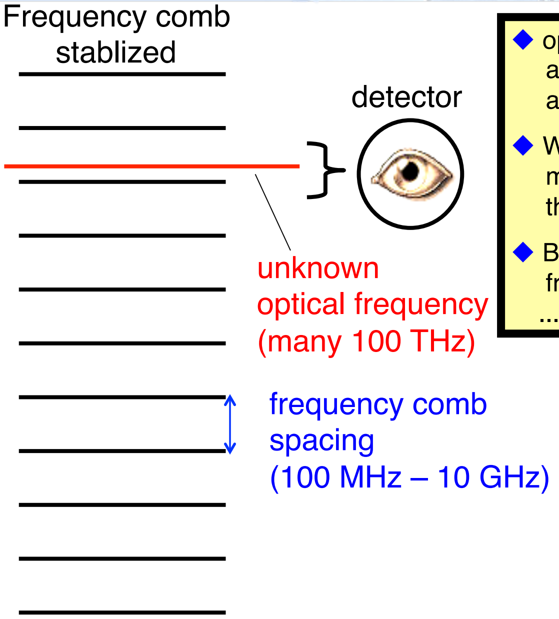
beat signal

Tuning fork Nr. 2 at the frequency f_2

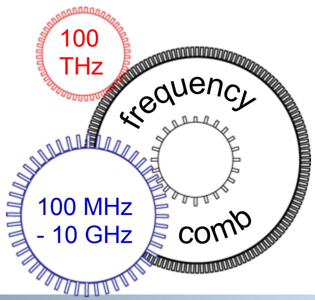


The superposition of two frequencies f_1 und f_2 detected with a photo detector gives a beat signal at the difference frequency $f_1 - f_2$

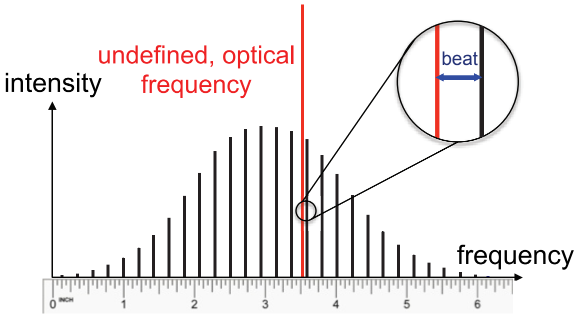
How can you measure optical frequencies?



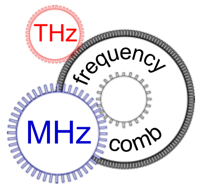
- optical frequencies too high for a direct measurement with high accuracy
- With frequency comb: measure unknown frequency with the beat signal on the detector
- Beat signal at less than half of the frequency comb spacing ... can be measured!



Optical Frequency Combs

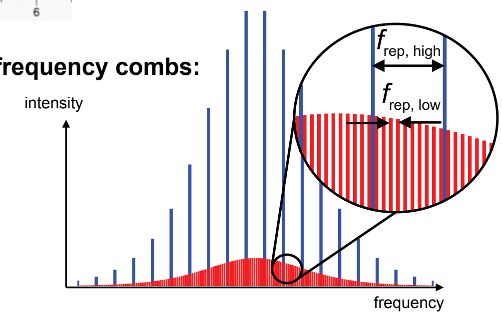


phase-stable link:
optical to microwave

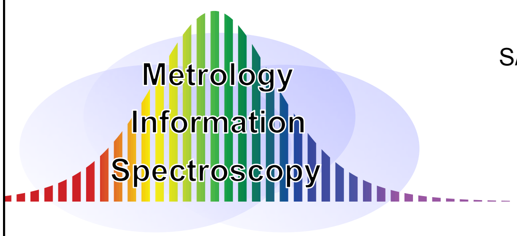


High gigahertz pulse repetition rate frequency combs:

- higher power per mode
- easier to access individual lines
- more compact laser system



Frequency combs: need for high repetition rates



S/N in nearly all applications is limited by available **power per comb line**

power per line ~ **average power** x **repetition rate**

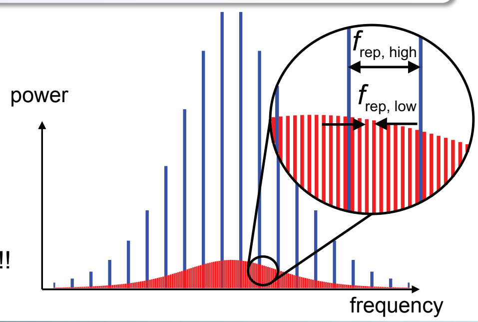
Higher repetition rates increase the power in each comb line

example with 100-fs pulses:

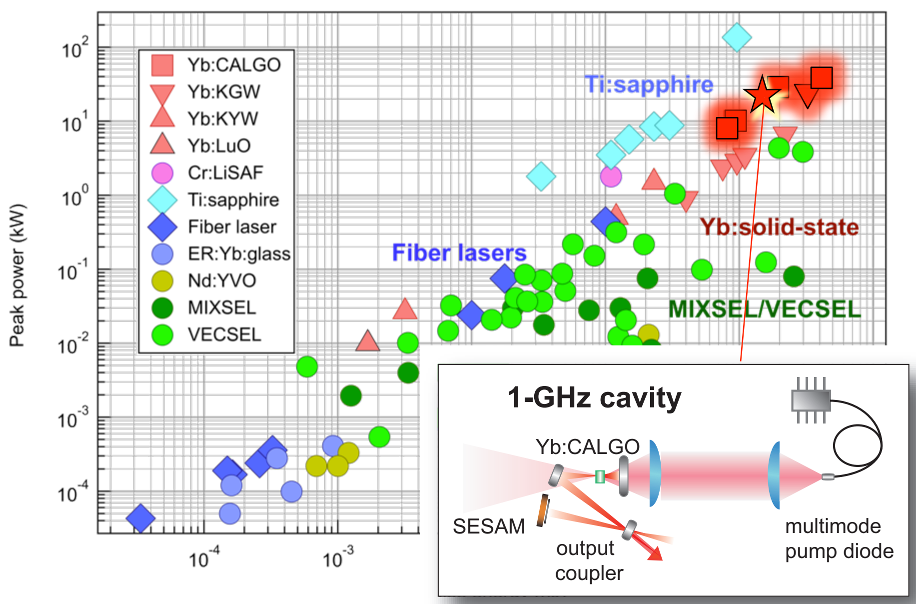
f_{rep} = 5 GHz, $P_{average}$ = 4 W:

average power per line ≈ **1.86 mW**
(incl. lines 20 dB below maximum)

at 100 MHz this requires $P_{average}$ = 200 W!!

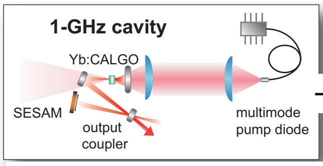


GHz oscillators w/o amplification or compression



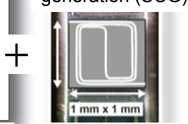
Benefits of Si_3N_4 waveguide

First self-referenced frequency comb based on SCG in Si_3N_4 Chip

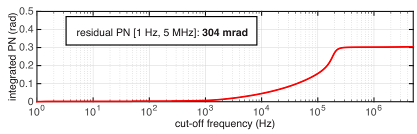


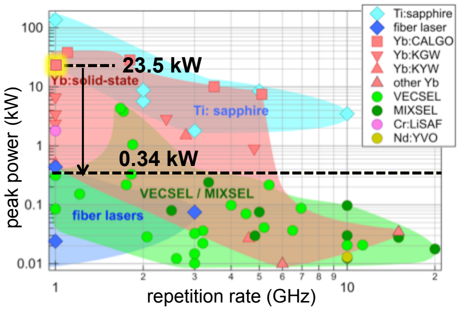
SESAM modelocked diode-pumped solid-state laser (no amplifiers)

Supercontinuum generation (SCG)

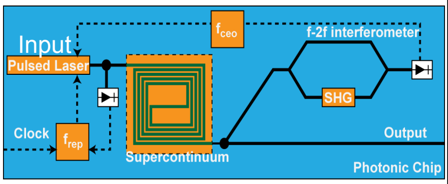


Si_3N_4 waveguide 7.5 mm long





- First CEO-Stabilization with extra-cavity SCG requiring **< 1kW**
- **304 mrad: Lowest RPN** of any stabilized gigahertz diode-pumped solid state laser to date
- CMOS-compatible and integration



A. Klenner et al., *Optics Express* **24**, 11043, 2016
Collaboration with M. Lipson and A. L. Gaeta

Frequency comb stabilization with microresonators ... is challenging

LETTERS
PUBLISHED ONLINE: 6 JUNE 2016 | DOI: 10.1038/NPHOTON.2016.105
nature photonics

Phase-coherent microwave-to-optical link with a self-referenced microcomb

Pascal Del'Haye[1,2]*, Aurélien Coillet[2†], Tara Fortier[2], Katja Beha[2], Daniel C. Cole[2], Ki Youl Yang[3], Hansuek Lee[3†], Kerry J. Vahala[3], Scott B. Papp[2] and Scott A. Diddams[2]*

Precise measurements of the frequencies of light waves have become common with mode-locked laser frequency combs[1]. Despite their huge success, optical frequency combs currently remain bulky and expensive laboratory devices. Integrated photonic microresonators are promising candidates for comb generators in out-of-the-lab applications, with the potential for reductions in cost, power consumption and size[2]. Such advances will significantly impact fields ranging from spectroscopy and trace gas sensing[3] to astronomy[4], communications[5] and atomic time-keeping[6,7]. Yet, in spite of the remarkable progress shown over recent years[8–10], microresonator frequency combs ('microcombs') have been without the key function of direct *f*–2*f* self-referencing[1], which enables precise determination of the absolute frequency of each comb line. Here, we realize this missing element using a 16.4 GHz microcomb that is coherently broadened to an octave-spanning spectrum and subsequently fully phase-stabilized to an atomic clock. We show phase-coherent control of the comb and demonstrate its low-noise operation.

generates a phase-locked microcomb[24,25] with part of the comb light being detected by a fast photodiode to measure the repetition rate. The rest of the comb light is optimized in phase and amplitude using a liquid-crystal-based spatial light modulator to generate the shortest possible pulse at the input of a highly nonlinear fibre (HNLF 1 in Fig. 1a, input power ~150 mW). Note that this phase and amplitude optimization could be removed when using a single soliton microcomb generator, as demonstrated in Si_3N_4 and MgF_2 (refs 9,26). After another step of quadratic dispersion compensation and amplification to an average optical power of ~4 W, the 16.4 GHz pulse train of <200 fs pulses is sent into a second hybrid nonlinear optical fibre[27] that broadens the optical spectrum to an octave (Fig. 1b). The octave-spanning spectrum is sent to an *f*–2*f* interferometer for generation of the carrier envelope offset beat note. The *f*–2*f* interferometer includes a variable time delay for the long wavelength part of the spectrum in order to achieve a temporal overlap with the short wavelength end of the spectrum. Nonlinear frequency doubling of the 2.22 µm spectral region to 1.11 µm is achieved in a 10-mm-long periodically poled lithium

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This "microcomb" needs a high power single frequency cw pump laser!

June 2016 first microcomb stabilization:
16.4 GHz microcomb not broad enough for f-2f self-referencing
needs single frequency cw pump laser, 3 optical amplifiers, 2 highly nonlinear fibers and a pulse shaper

... is this still compact?
How does this compare to laser frequency combs?
See for example: Postdeadline Talk PD-1.1, stabilized dual comb modelocked laser

demonstrate its low-noise operation.
1.11 µm is achieved in a 10-mm-long periodically poled lithium

ETH zürich

Which publications started the frequency comb revolution?

H. R. Telle, G. Steinmeyer, A. E. Dunlop, J. Stenger, D. H. Sutter, and U. Keller,
"Carrier-envelope offset phase control: A novel concept for absolute optical frequency measurement and ultrashort pulse generation,"
Appl. Phys. B **69**, 327-332 (1999)

D. J. Jones, S. A. Diddams, J. K. Ranka, A. Stentz, R. S. Windeler, J. L. Hall, and S. T. Cundiff,
"Carrier-envelope phase control of femtosecond mode-locked lasers and direct optical frequency synthesis,"
Science **288**, 635-639 (2000).

A. Apolonski, A. Poppe, G. Tempea, C. Spielmann, T. Udem, R. Holzwarth, T. W. Hänsch, and F. Krausz,
"Controlling the phase evolution of few-cycle light pulses,"
Phys. Rev. Lett. **85**, 740-743 (2000)

The first paper in 1999 was explicitly referenced in "Advanced information for the Nobel Prize in Physics 2005"
More info and Nobel information PDF-file on http://www.ulp.ethz.ch/research/frequency-combs.html

If you work in this field, please read and reference these three papers from different groups who all made key enabling and pioneering contributions. This simply follows good scientific practice. Thank you.

ETH zürich

Outline

- Why and how was the SESAM invented?
- Challenge: need fast saturable absorber for shorter pulses
  Solution: Defect management (low temperature growth, AlAs traps, surface traps ...)
- Problem: Q-switching instabilities for passively modelocked solid-state lasers
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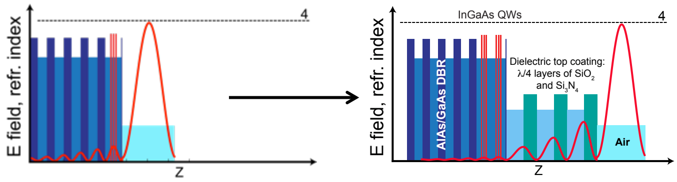
  Solution: Carrier envelope offset frequency (CEO) stabilization
  ... this solution also enabled the frequency metrology revolution
- Modelocking and frequency metrology: stabilized frequency combs
- Frontier lasers need different SESAM design parameters ... ongoing research.

Ultrafast Laser Physics ETH zürich

Frontier lasers need different SESAM parameters

- **High average power** (i.e. 100 W to 1 kW) ultrafast solid-state laser:
  SESAM modelocked thin disk lasers (TDLs)
  high saturation fluence, large mode size (special mounting techniques), faster saturable absorber

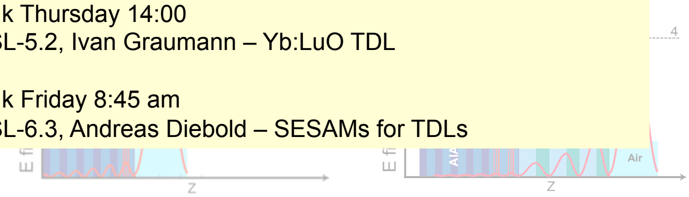


- **Gigahertz femtosecond** diode-pumped solid-state lasers:
  SESAM modelocked Yb-doped lasers, best results with Yb:CALGO
  low saturation fluence, faster saturable absorbers (AlAs barrier)
- **Gigahertz optically pumped semiconductor disk lasers (SDLs)**:
  SESAM modelocked VECSELs, MIXSELs
  fully integrated structure of gain and absorber in one wafer, faster saturable absorber, broadband close to zero GDD, medium saturation fluence

... and in all cases low non-saturable losses: $\Delta R_{ns} << \Delta R$

Frontier lasers need different SESAM parameters

- **High average power** (i.e. 100 W to 1 kW) ultrafast solid-state laser:
  SESAM modelocked thin disk lasers (TDLs)
  high saturation fluence, large mode size (special mounting techniques), faster
  satu



Talk Thursday 14:00
SSL-5.2, Ivan Graumann – Yb:LuO TDL

Talk Friday 8:45 am
SSL-6.3, Andreas Diebold – SESAMs for TDLs

- **Gigahertz femtosecond** diode-pumped solid-state lasers:
  SESAM modeloc
  low saturati

Talk Tuesday 11:15 am
SSL-1.3, Aline Mayer – mid-IR frequency comb

- **Gigahertz optically pumped semiconductor disk lasers (SDLs)**:
  SESAM modelocked VECSELs, MIXSELs
  fully integrat
  absorber, br

Talk Friday 8:30 am
SSL-6.2, Sandro Link – record low pulse duration of SDLs
and Poster Thursday PO-3.21

... and in all cases low non-saturable losses: $\Delta R_{ns} << \Delta R$

ETH zürich

More info on the web ...

- Web page of Prof. Ursula Keller at ETH Zurich: http://www.ulp.ethz.ch
- All papers are available to download as PDFs: http://www.ulp.ethz.ch/publications/journal-articles.html
- SESAM and milestones: http://www.ulp.ethz.ch/research/sesam.html
- Ultrafast solid-state laser: get started with the book chapter ... http://www.ulp.ethz.ch/research/ultrafast-solid-state-lasers.html
- VECSEL and MIXSEL: http://www.ulp.ethz.ch/research/vecsel-mixsel.html
- Frequency combs: http://www.ulp.ethz.ch/research/frequency-combs.html
- Attoscience, Attoclock, Attoline:
  http://www.ulp.ethz.ch/research/attosecond-science.html
  http://www.ulp.ethz.ch/research/attoline.html
  http://www.ulp.ethz.ch/research/attoclock.html
- Viewgraphs to graduate lecture course: Ultrafast Laser Physics http://www.ulp.ethz.ch/education/lectures/ultrafast-laser-physics.html

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All these results only possible with a great group and dedicated work, good funding over many years

ULP - Ultrafast Laser Physics (Mission Statement)

www.ulp.ethz.ch

To explore and push the frontiers in ultrafast science and technology, using interdisciplinary understanding of the physics of lasers, semiconductors, and measurement technologies. Take this competitive know-how to understand and control fundamental charge and energy transport with atomic spatial and attosecond temporal resolution.

Ultrafast solid-state lasers

- High-power TDLs
- Semiconductor disk lasers
- High rep rate SSLs

Attosecond science

- OPCPA
- Attoline
- Attoclock (COLTRIMS)
- etc…

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