"20 years anniversary of the SESAM"

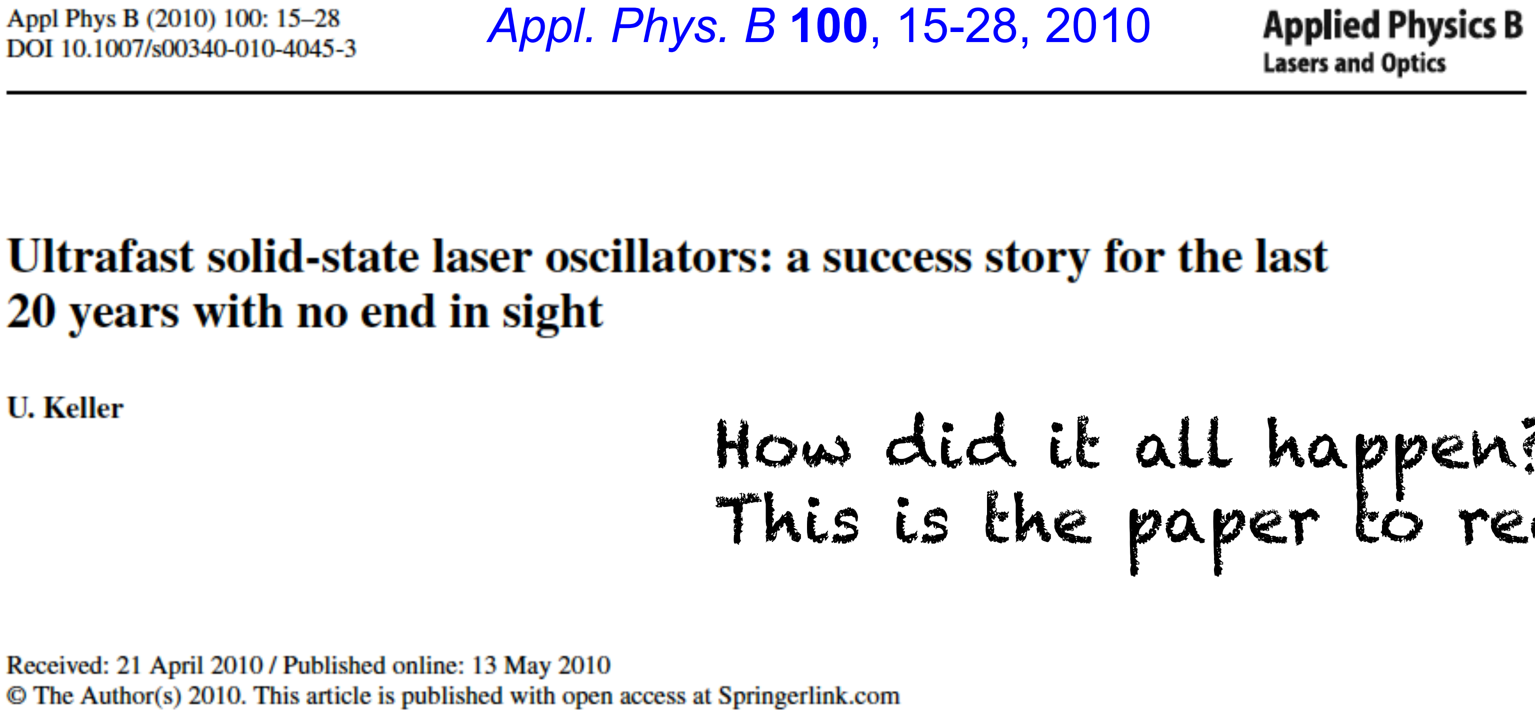
20 years of SESAM modelocked lasers:
a success story

Ursula Keller
Department of Physics, Institute for Quantum Electronics,
ETH Zurich, Switzerland

Plenary Talk

Advanced Laser Technologies, ALT 2012
2.-6. Sept. 2012, Thun, Sitzerland

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

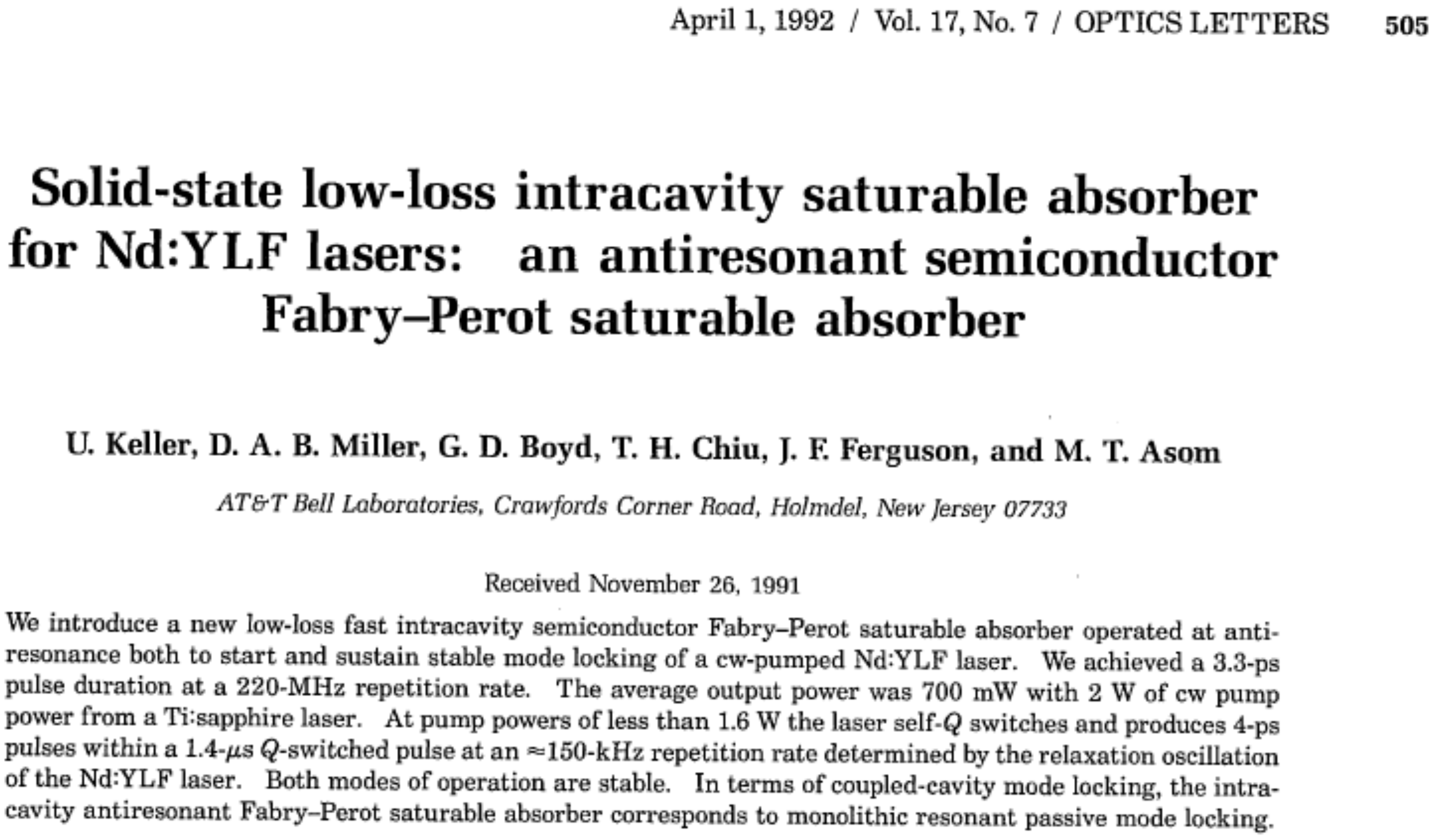
How did it all happen?
This is the paper to read …

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.

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

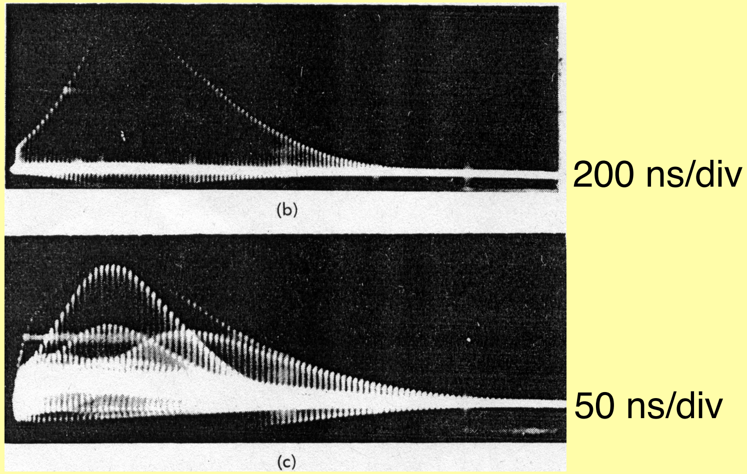
We introduce a new low-loss fast intracavity semiconductor Fabry–Perot saturable absorber operated at antiresonance both to start and sustain stable mode locking of a cw-pumped Nd:YLF laser. We achieved a 3.3-ps pulse duration at a 220-MHz repetition rate. The average output power was 700 mW with 2 W 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

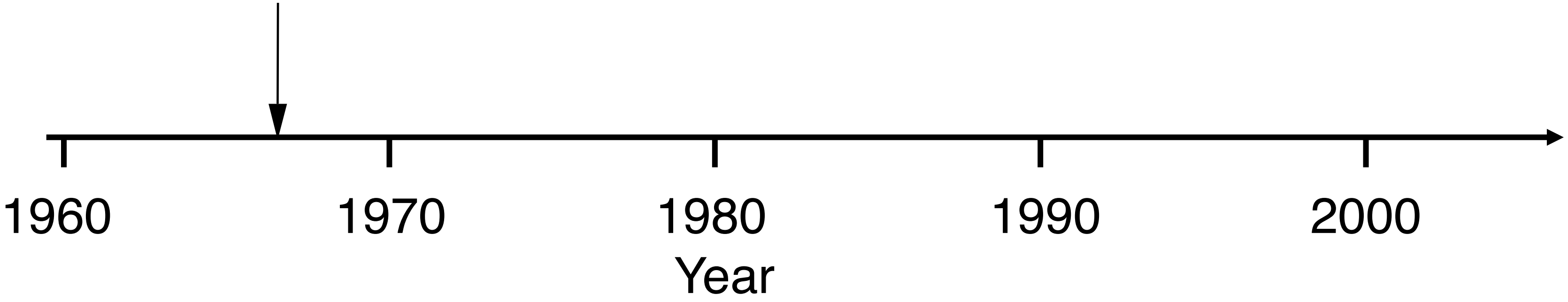
A. J. De Maria, D. A. Stetser, H. Heynau
Appl. Phys. Lett. **8**, 174, 1966



Nd:glass
first passively modelocked laser
Q-switched modelocked

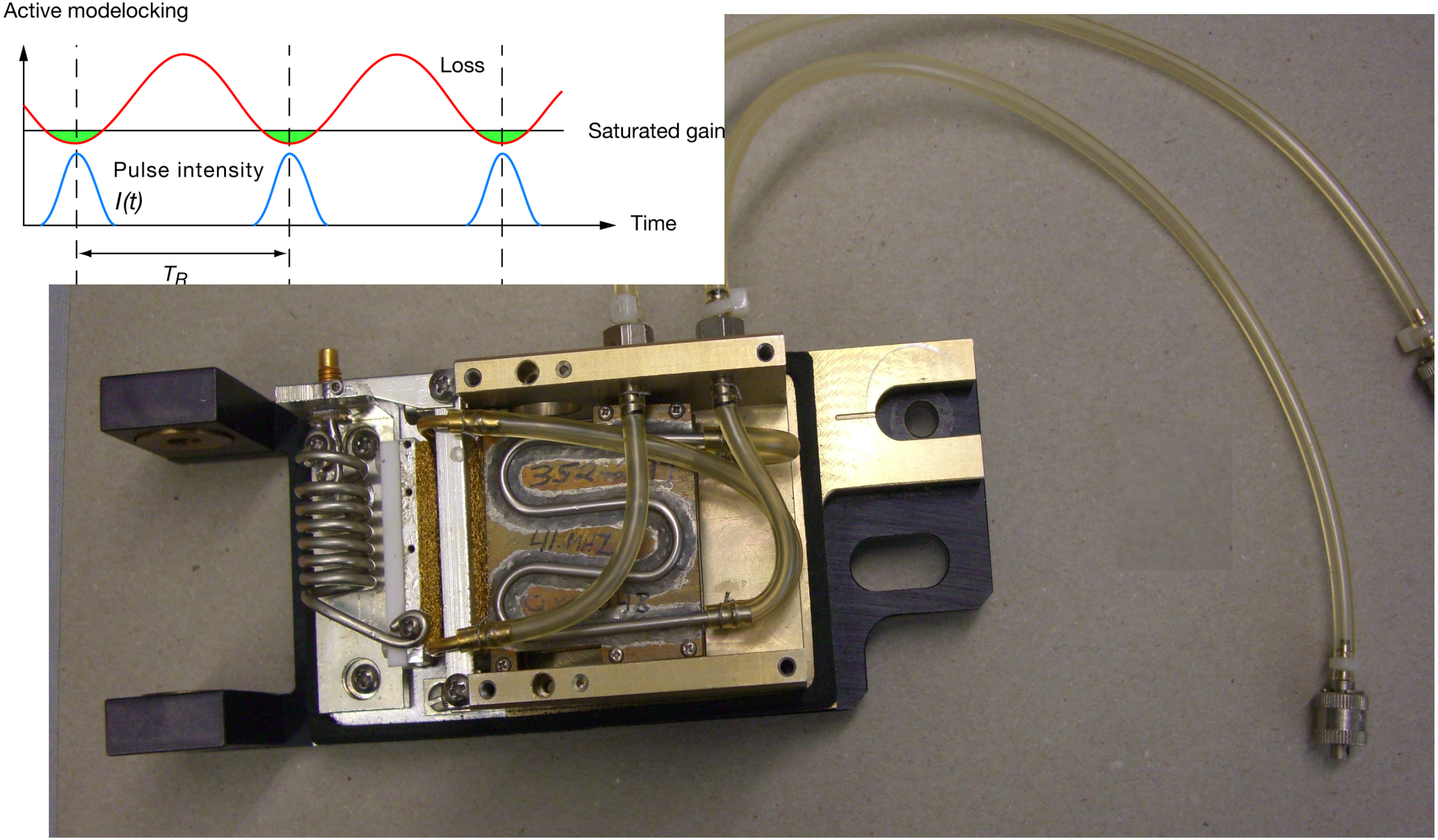
Q-switching problem in passively modelocked solid-state lasers:

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



Flashlamp-pumped
solid-state lasers

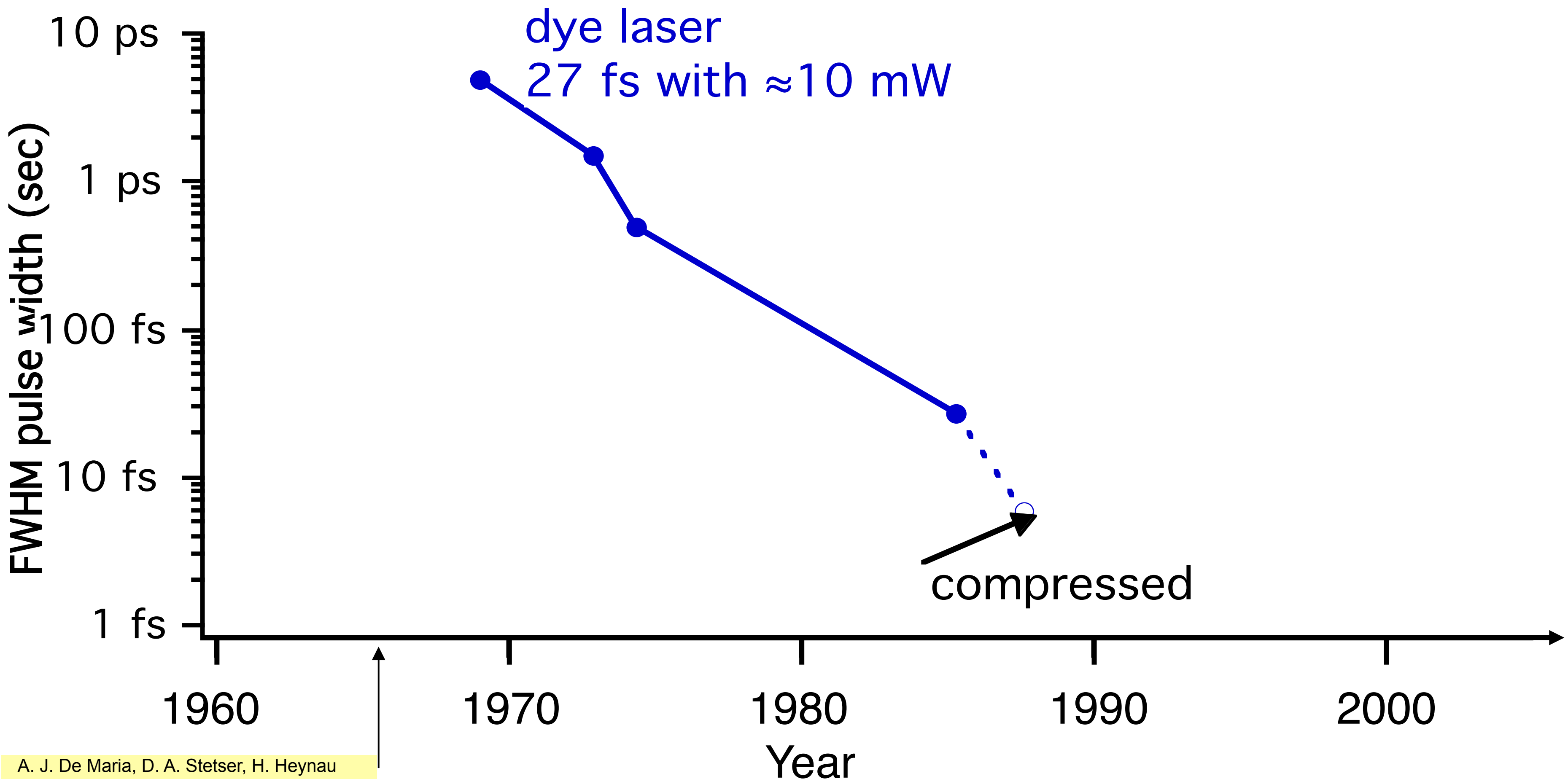
Active Modelocking



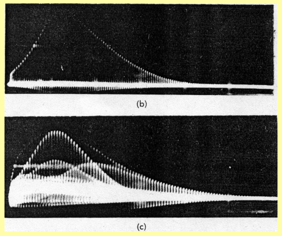
acousto-optic loss modulator

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



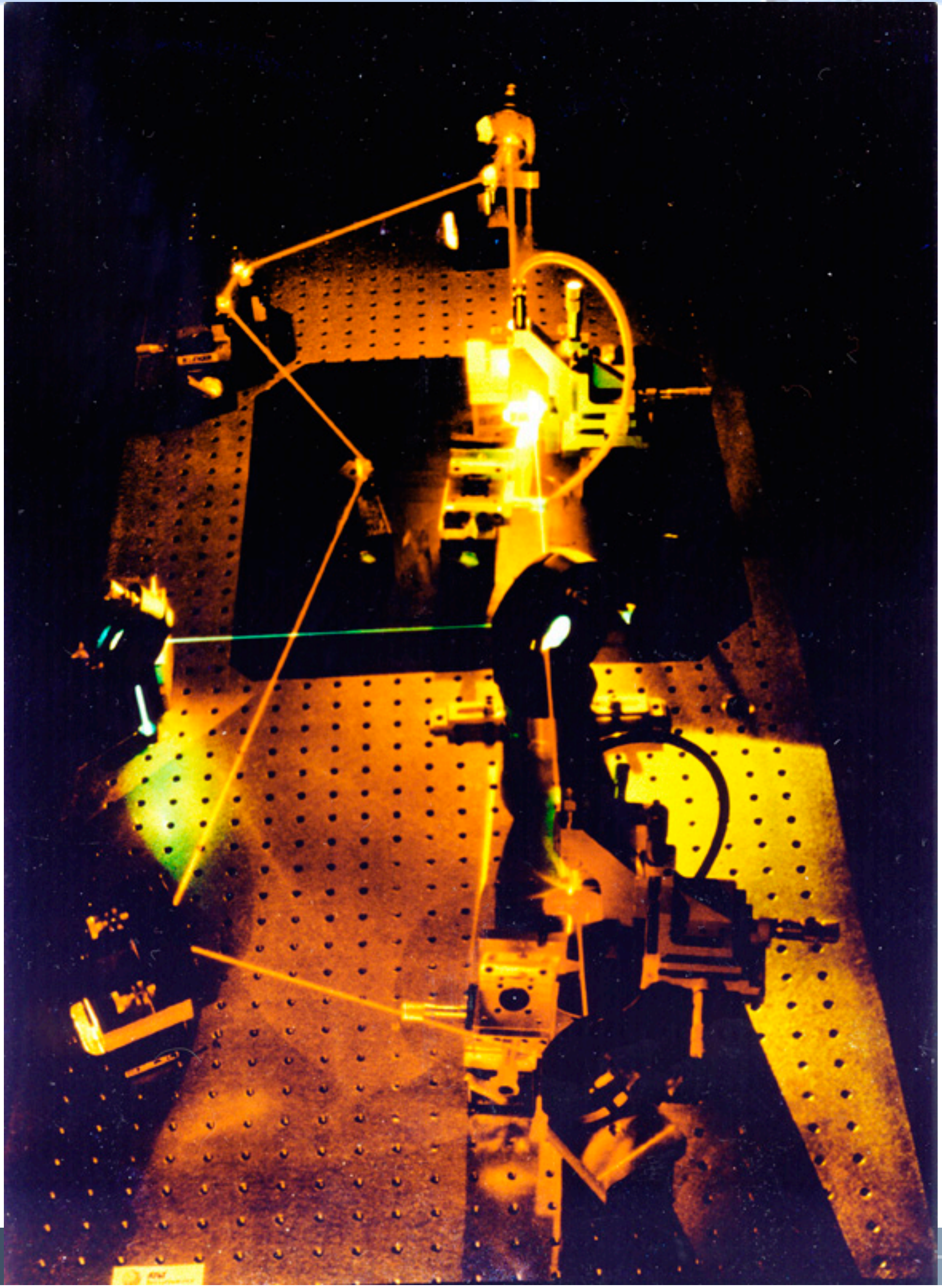
Nd:glass
first passively modelocked laser
Q-switched modelocked

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

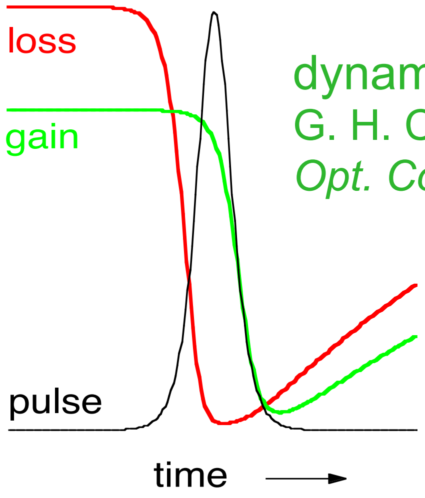
J. A. Valdmanis et al., Opt. Lett. 10, 131, 1985 (27 fs)

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)

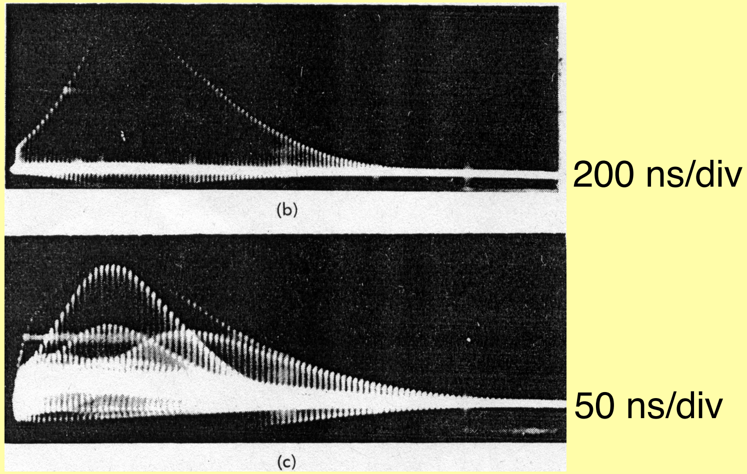


dynamic gain saturation
G. H. C. New
Opt. Commun. **6**, 188, 1972

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



Nd:glass
first passively modelocked laser
Q-switched modelocked

Q-switching instabilities continued to be a problem until 1992

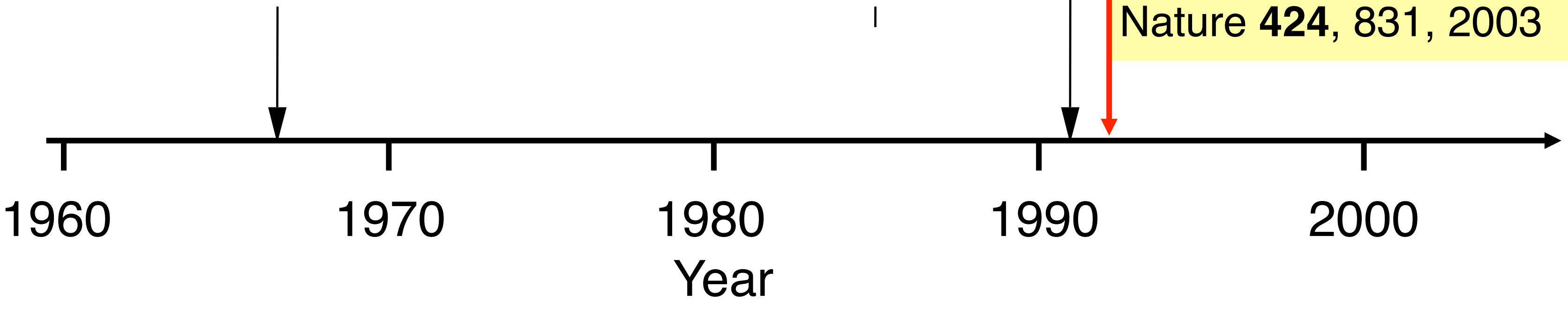
SESAM

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

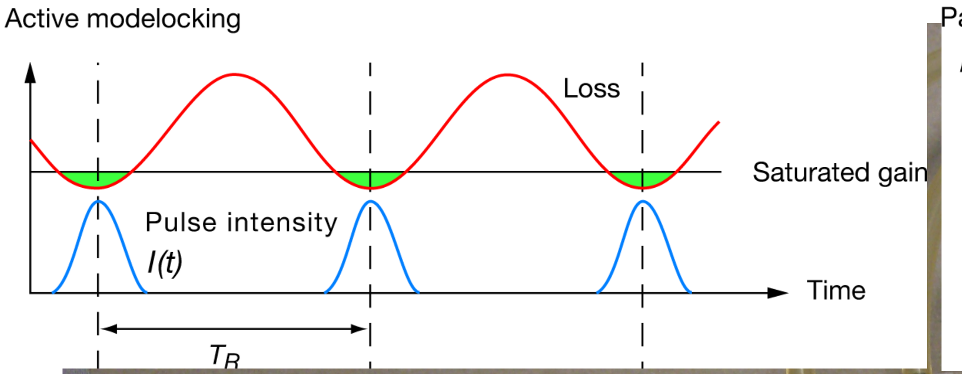
KLM

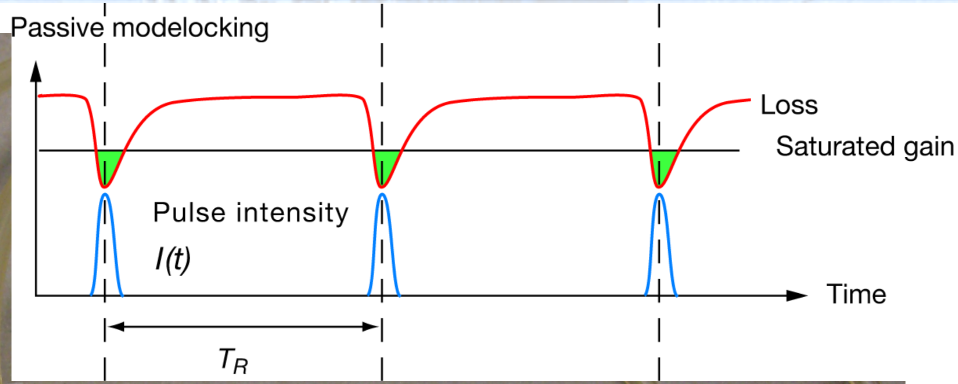


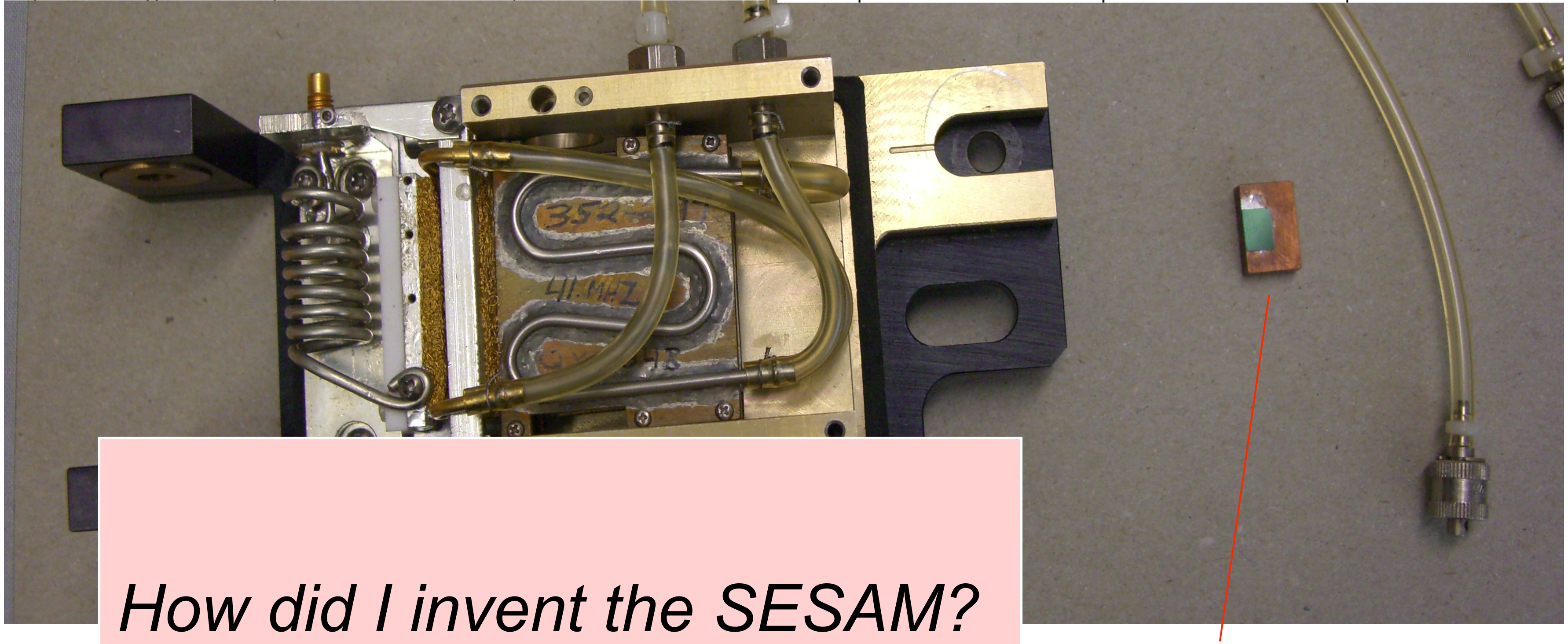
Flashlamp-pumped solid-state lasers

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

Innovation: before and after







How did I invent the SESAM?

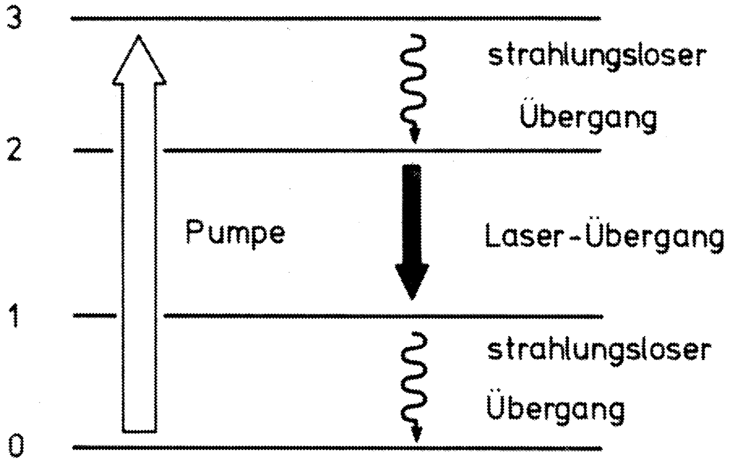
SESAM modelocker

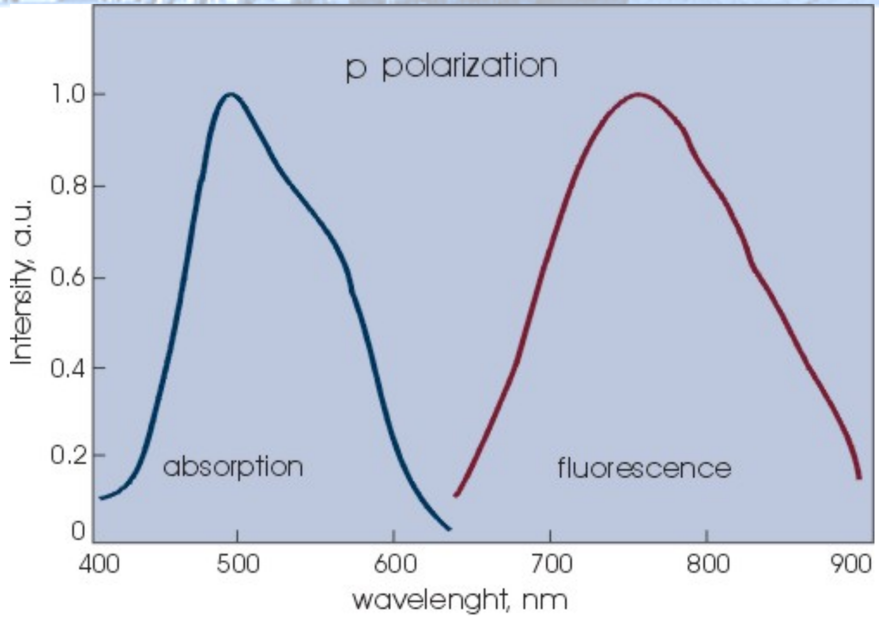
ac

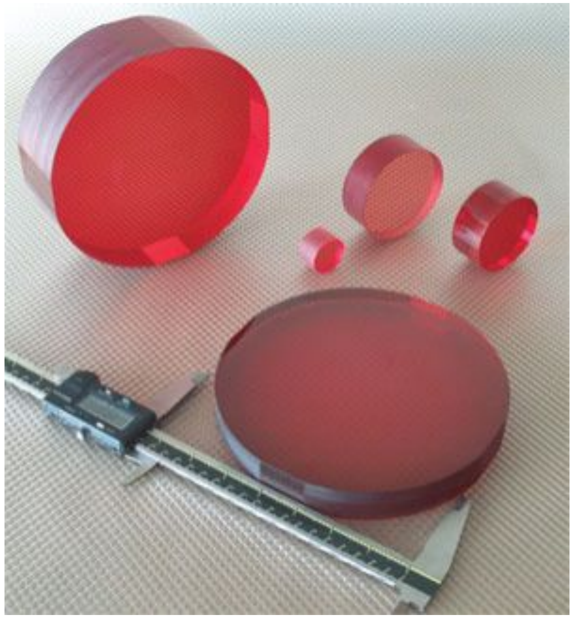
ne

Ti^{3+}:Saphir Laser

4-Niveau-System

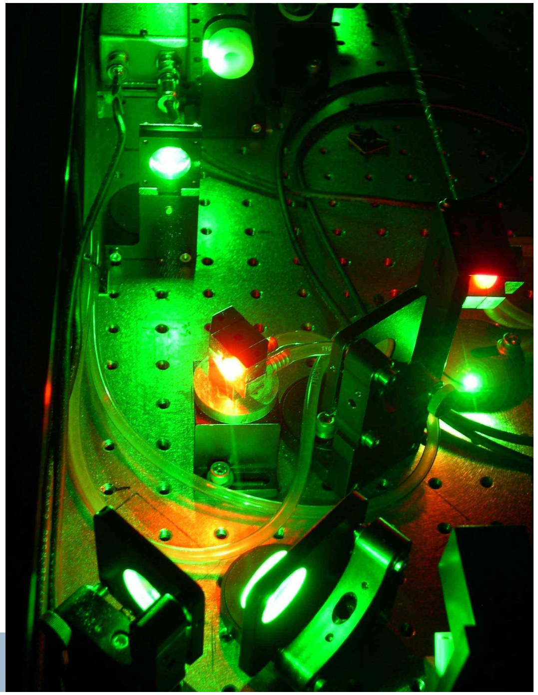






Ti:Saphir Laser
1982

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

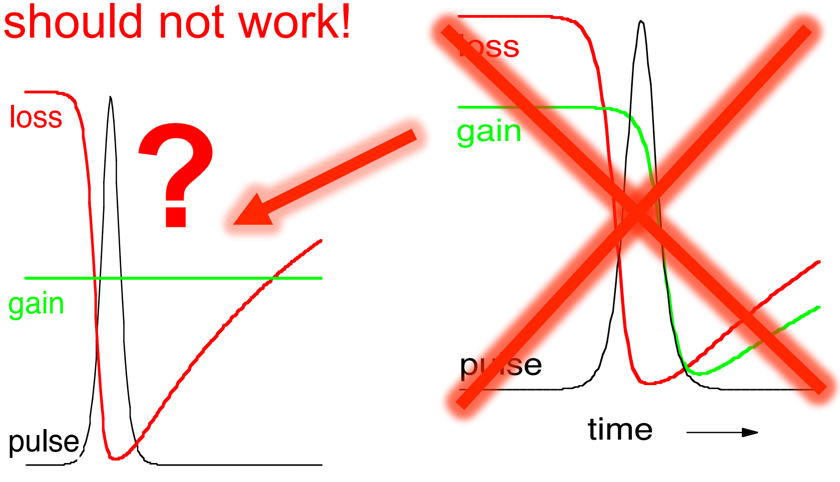
Explained modelocking as a "coupled cavity modelocking effect" between two transverse modes

"CPM Ti:sapphire laser"

Postdeadline Paper Ultrafast Phenomena 1990, Nr. PD11

Y. Ishida, N. Sarukura, H. Nakano

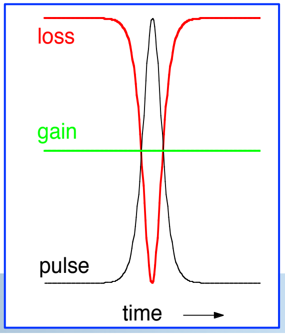
"used a dye saturable absorber inside the CPM Ti:sapphire laser"
... should not work!



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

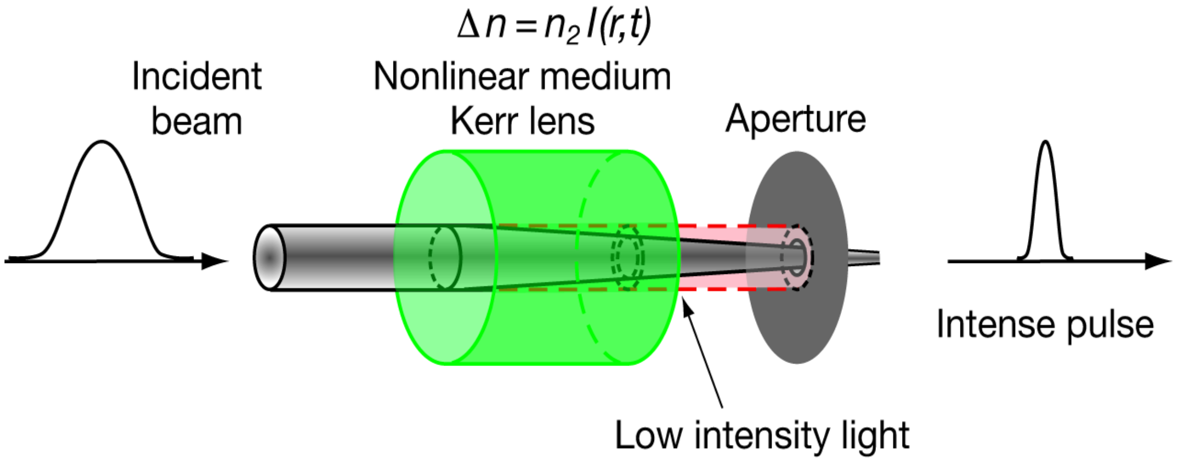
Optics Lett. **16**, 1022, 1991

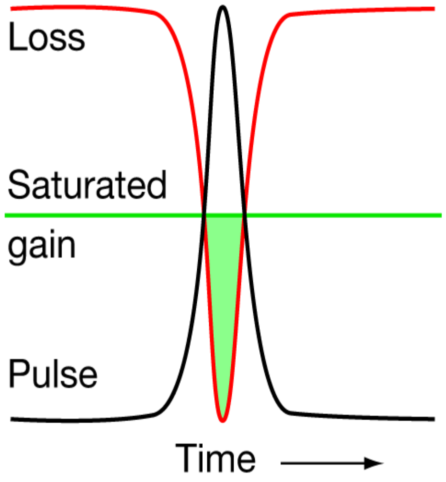
IEEE JQE **28**, 2123, 1992



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





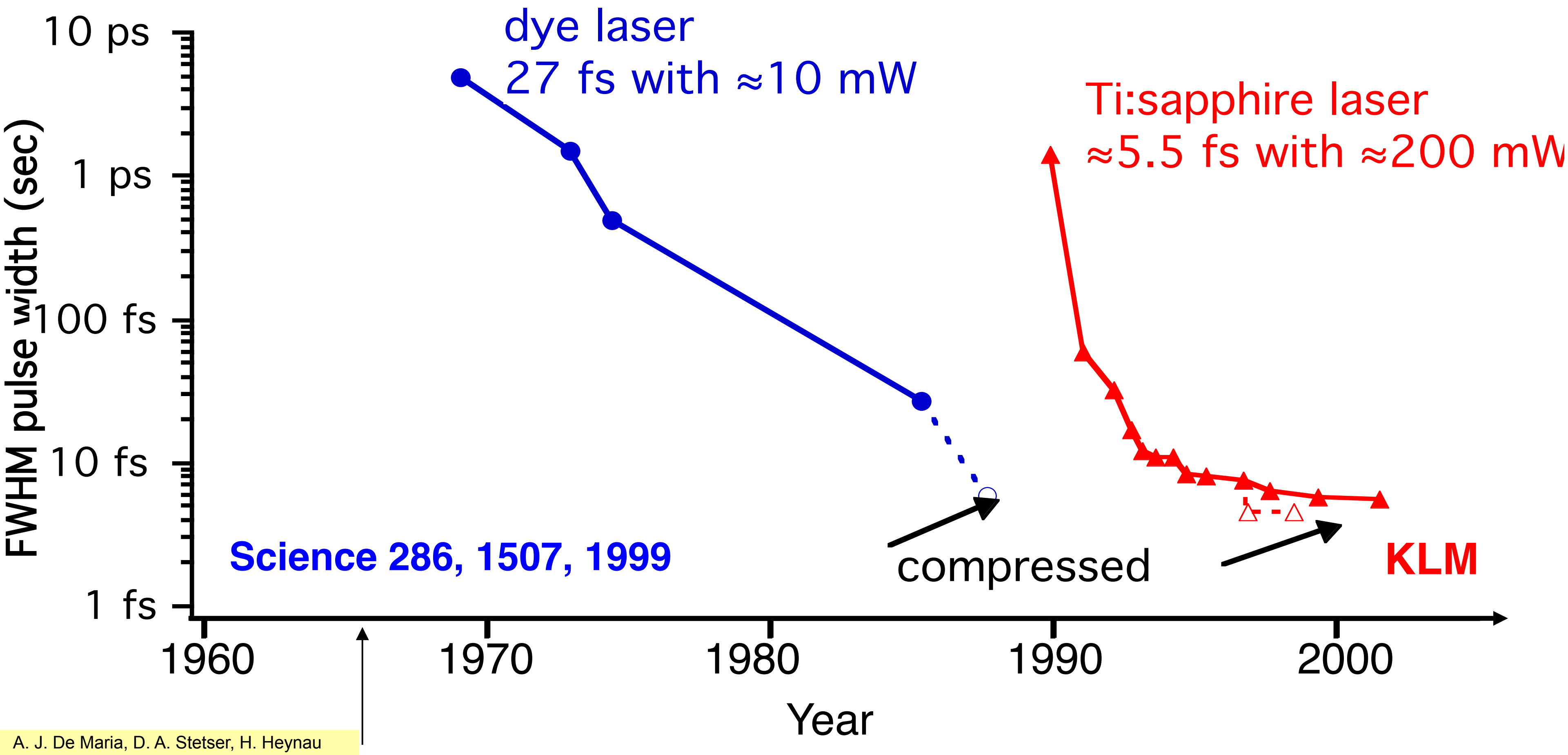
Advantages of KLM

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

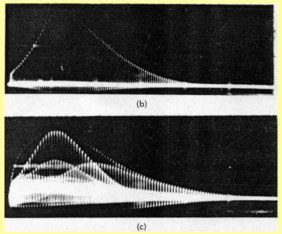
Disadvantages of KLM

- 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”?

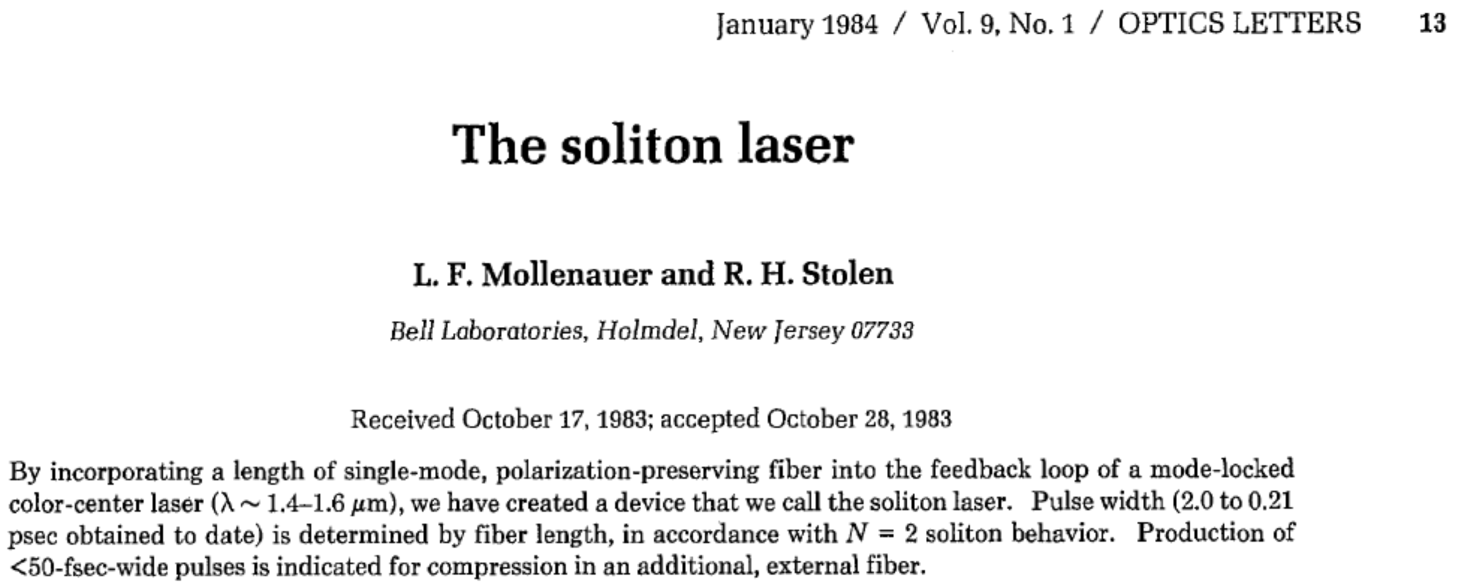
Remember the mind set at that time was:

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

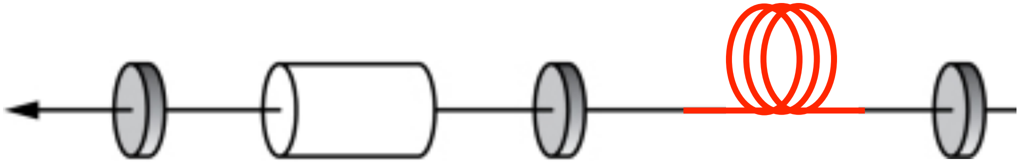
L. F. Mollenauer and R. H. Stolen

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

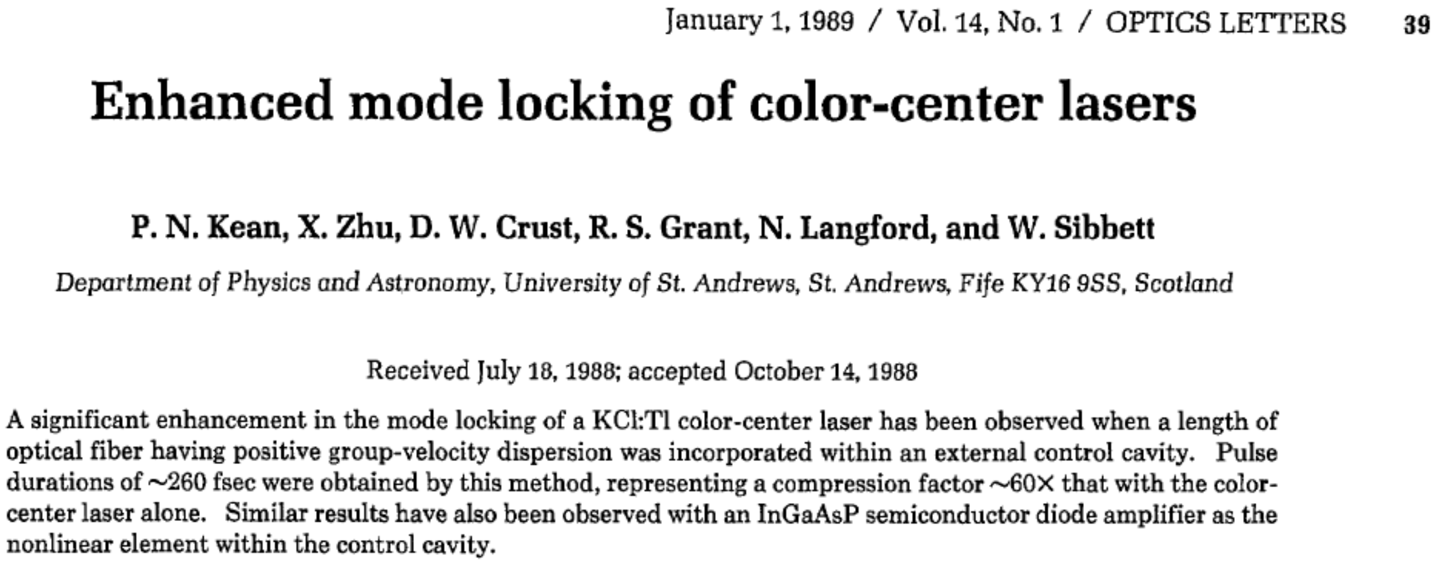


fiber with negative dispersion (GDD < 0)

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

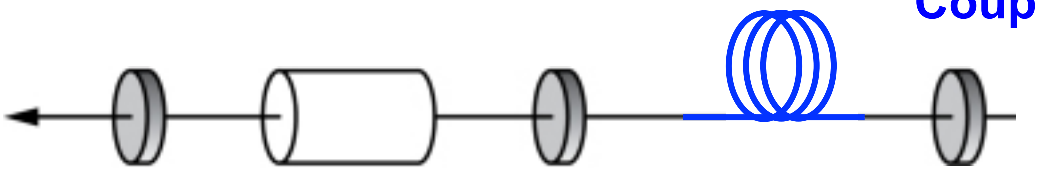
P. N. Kean, X. Zhu, D. W. Crust, R. S. Grant, N. Langford, and W. Sibbett

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)



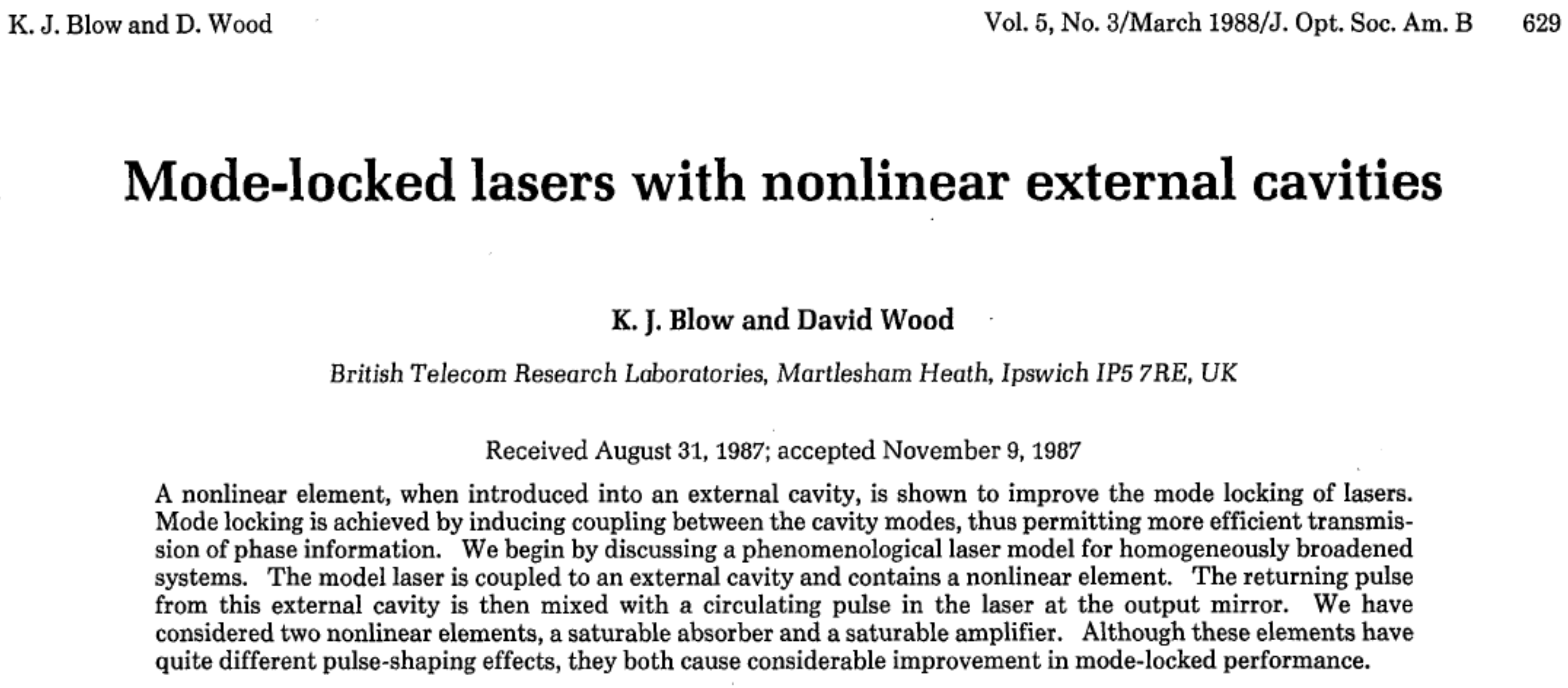
fiber with **positive** dispersion (GDD > 0)

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

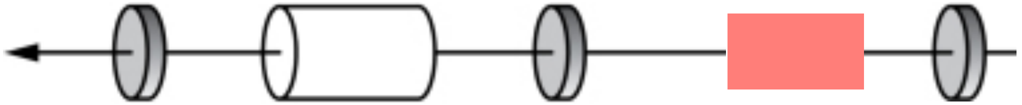
K. J. Blow and David Wood

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

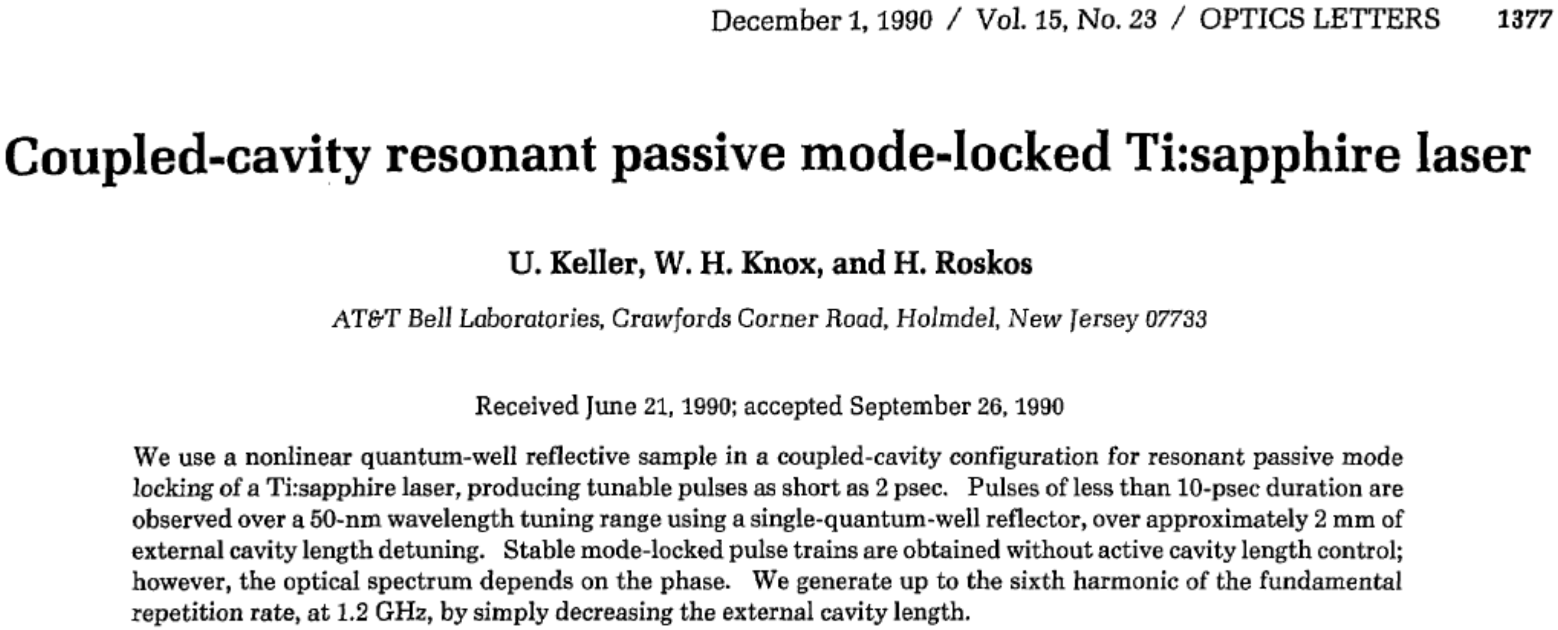


“any nonlinear element in the coupled cavity should shorten the pulse”

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

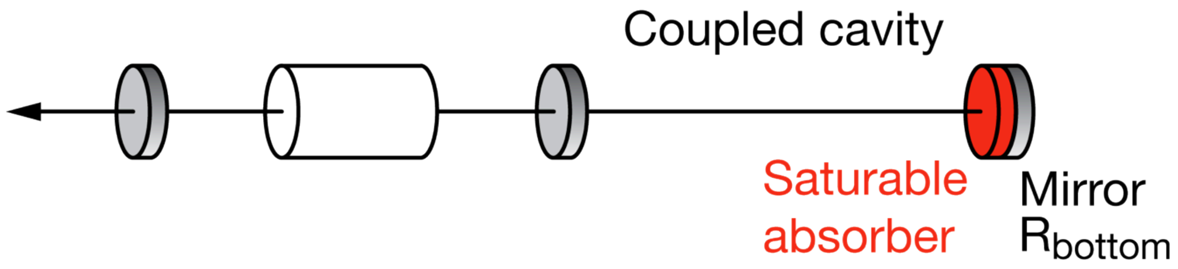
U. Keller, W. H. Knox, and H. Roskos

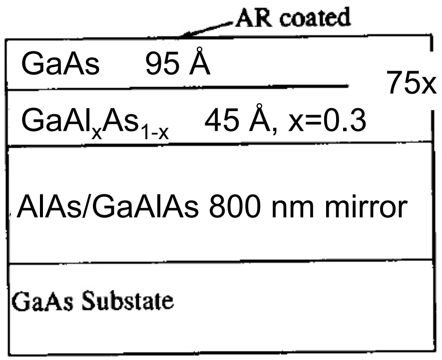
AT&T Bell Laboratories, Crawfords Corner Road, Holmdel, New Jersey 07733

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)



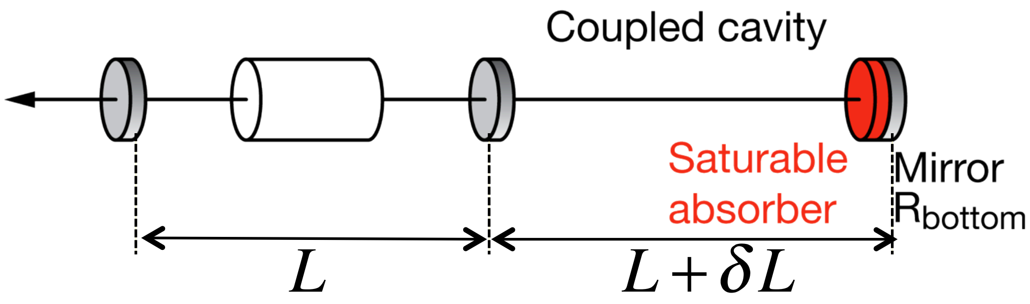


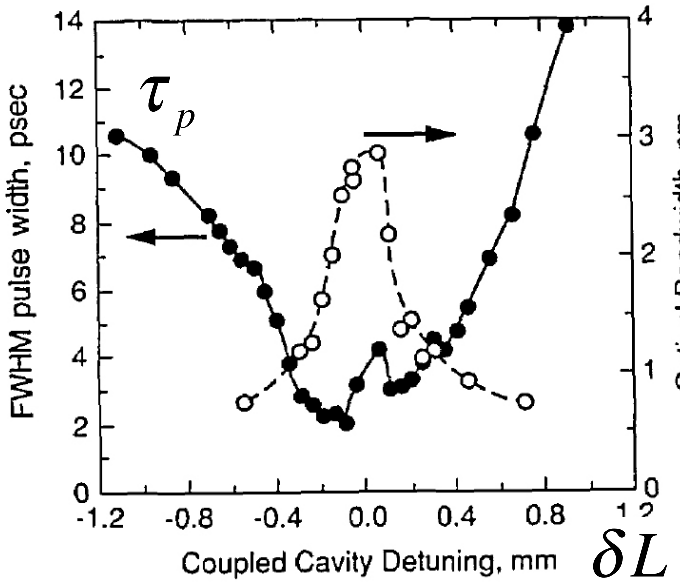
semiconductor saturable absorber (*“borrowed from my office neighbour Keith Goosen”*)
pulse compression in coupled cavity which shortens pulse in main cavity

Coupled Cavity Modelocking by Ursula Keller

1990

Resonant passive modelocking (RPM)





Surprise:

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

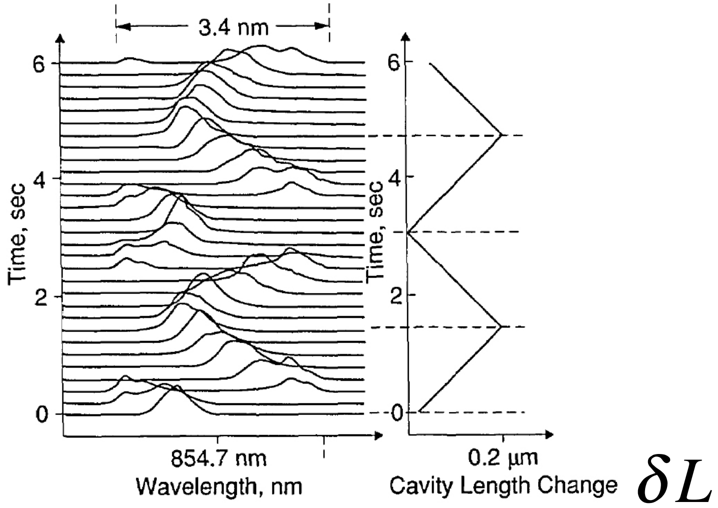
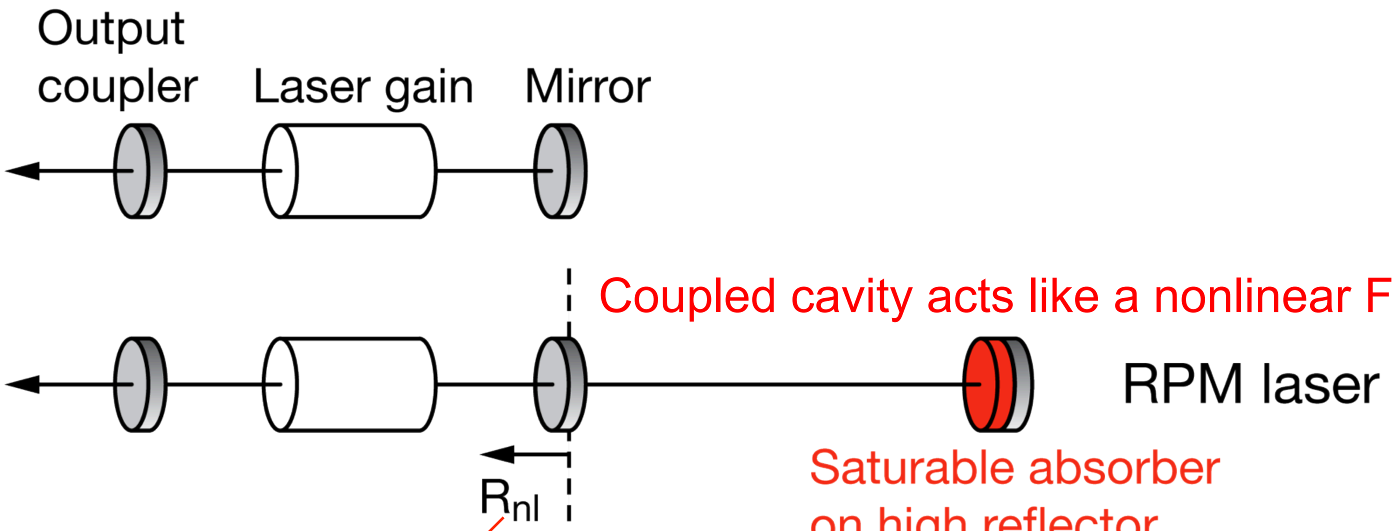


Fig. 3. Optical self-frequency shift versus the external cavity length detuning that ensures coherent superposition of the pulses at the coupling mirror.

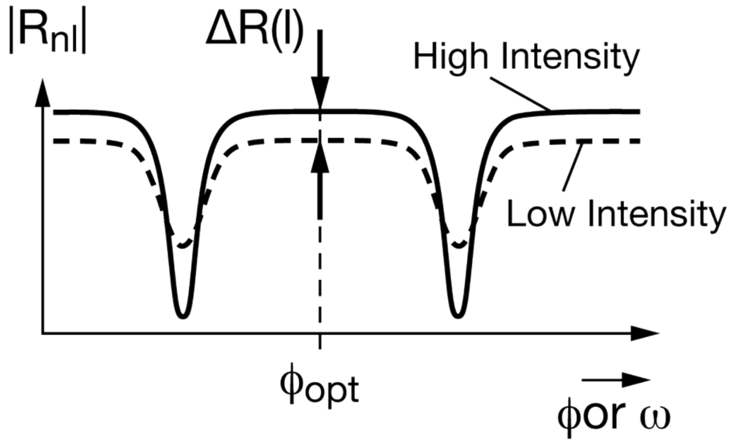
U. Keller et al., *Optics Lett.* **15**, 1377, 1990

Coupled Cavity Modelocking by Ursula Keller

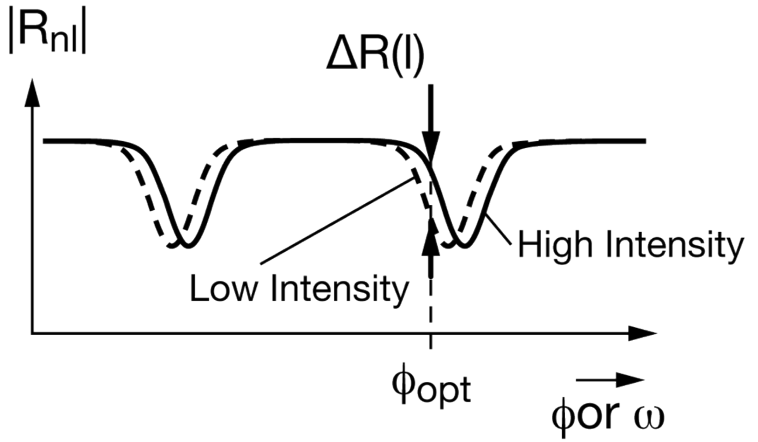


Coupled cavity acts like a nonlinear Fabry Perot (FP)

Saturable absorber
on high reflector

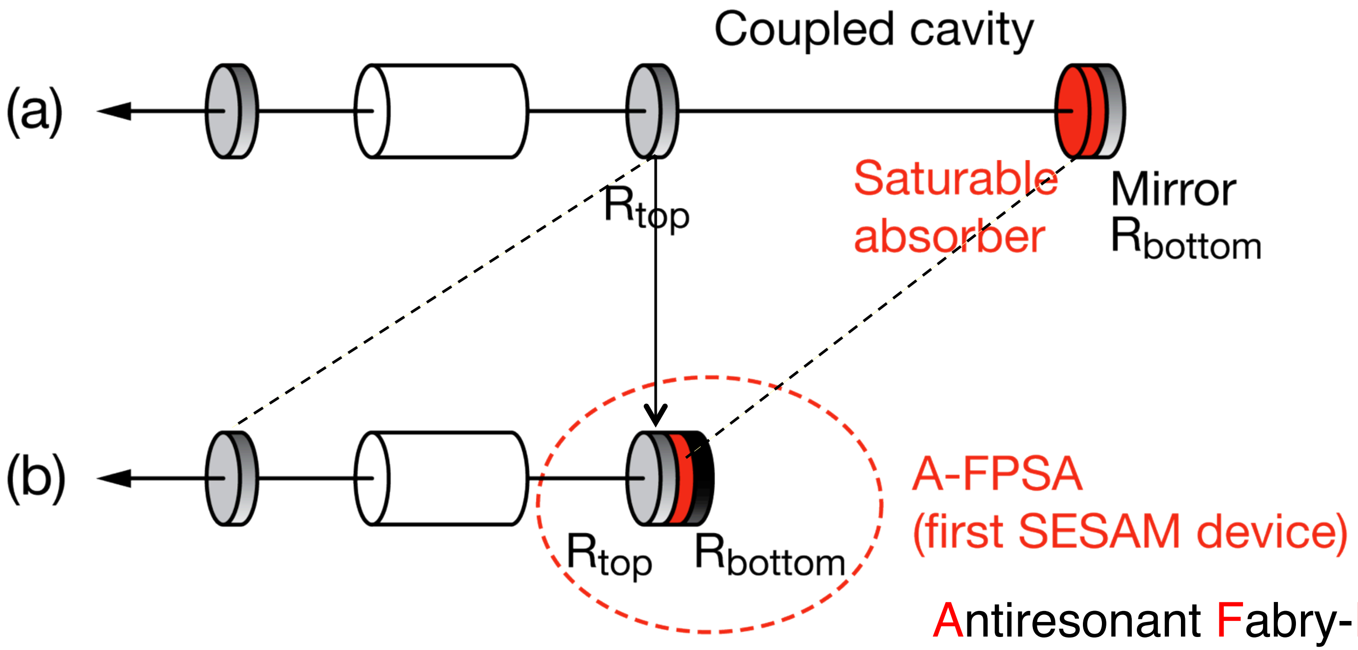


RPM = **amplitude (resonant)** nonlinearity
operated at maximum FP reflectivity
requires **no** cavity length stabilization



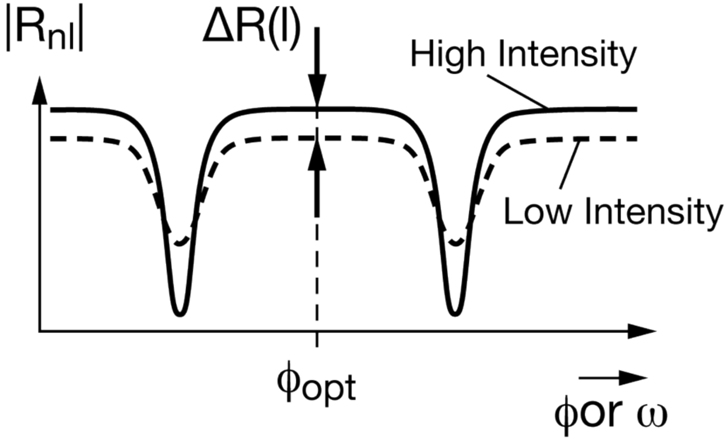
APM = **phase** nonlinearity
operated **not** at maximum FP reflectivity
requires cavity length stabilization

Invention of the first SESAM device: A-FPSA



Antiresonant Fabry-Perot Saturable Absorber (A-FPSA)

Example: *Opt. Lett.* **18,** 217, 1993



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

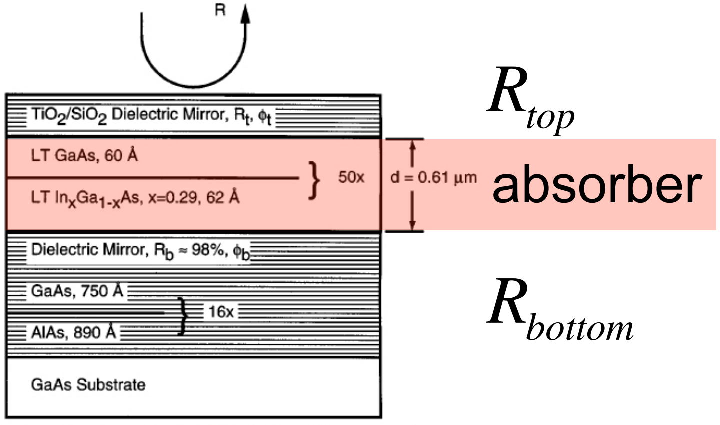
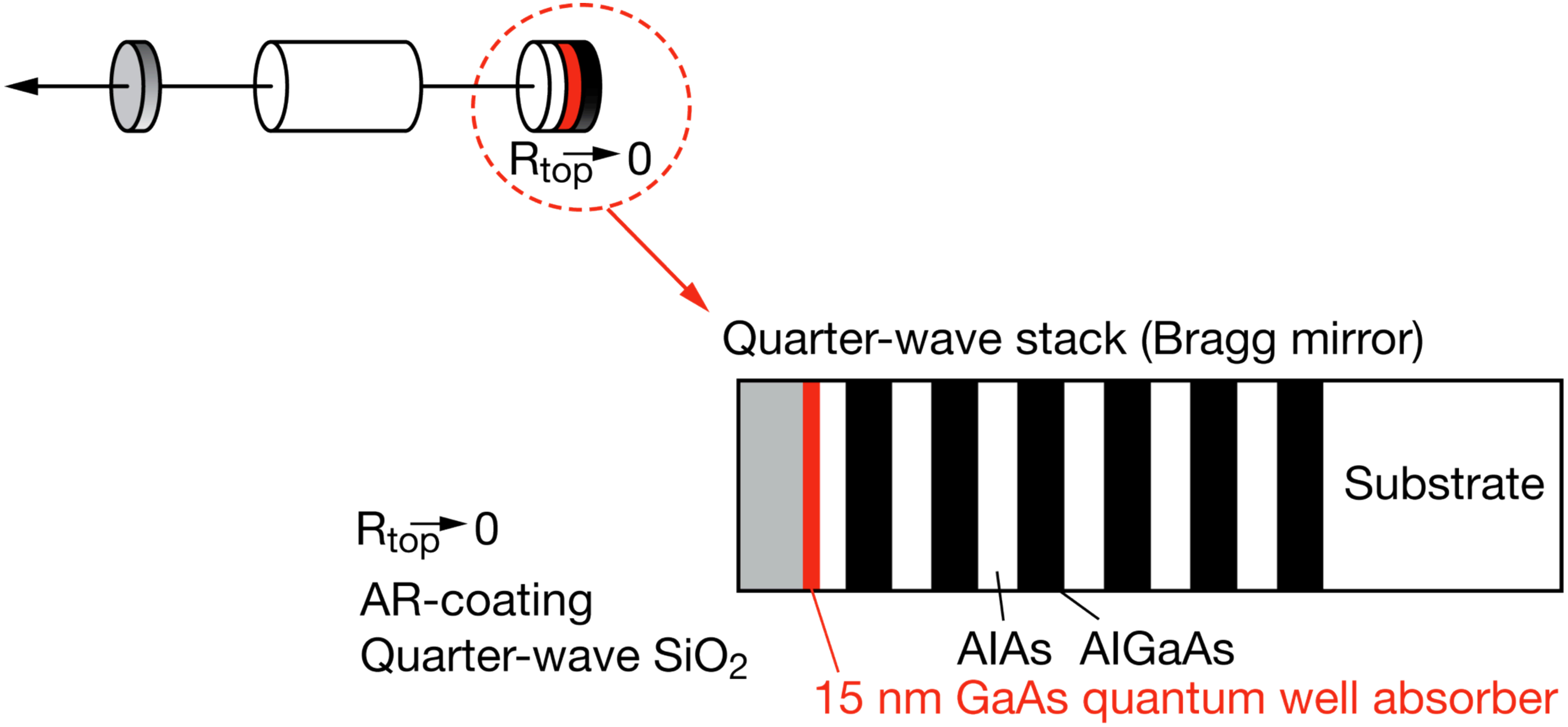


Fig. 1. Structure of an A-FPSA designed for an operation wavelength of ≈1 µm.

Scaling A-FPSA towards a single QW SESAM

1995

Adjustable parameter: top reflector

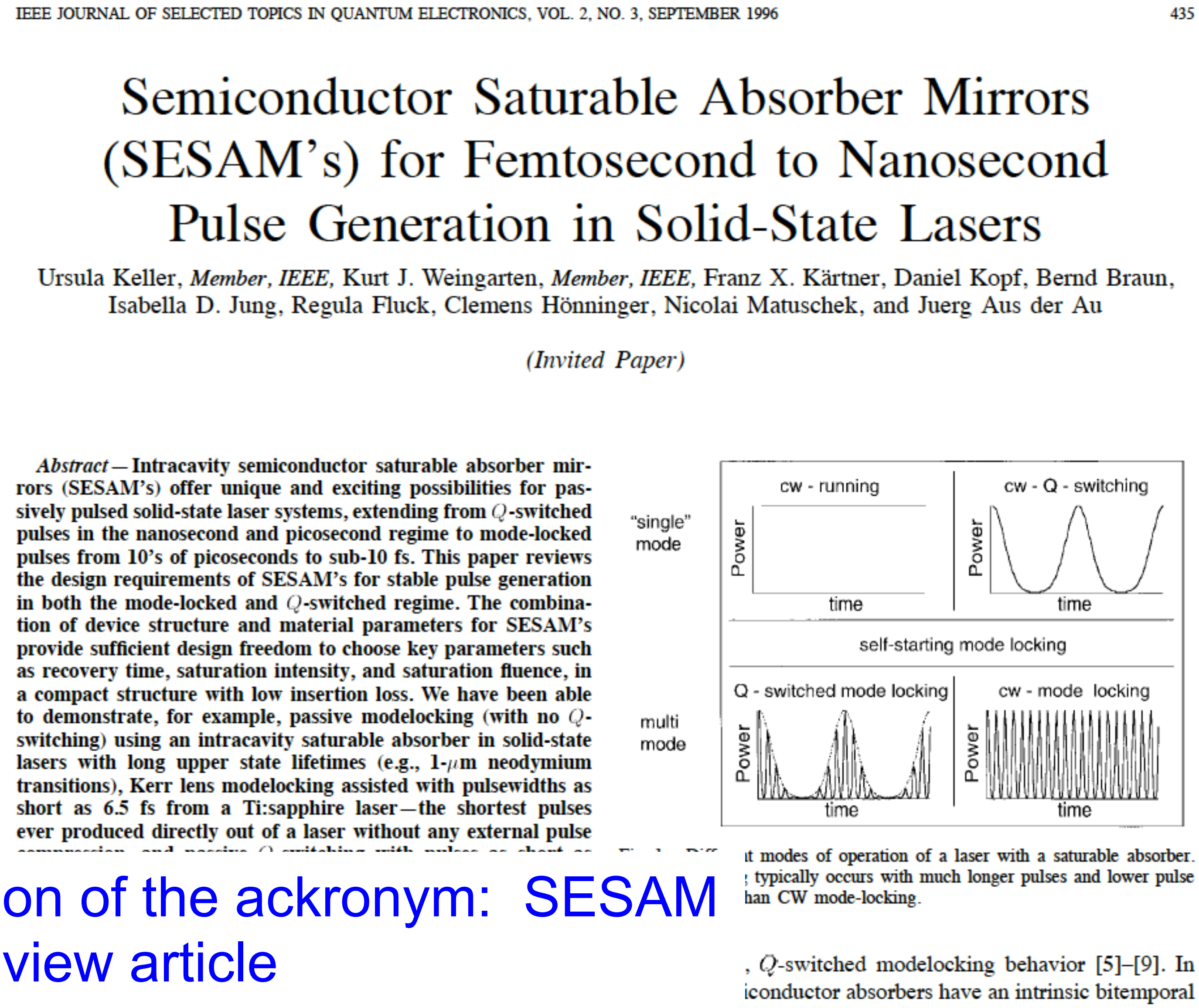


Single 15 nm GaAs quantum well embedded inside a Bragg mirror

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**

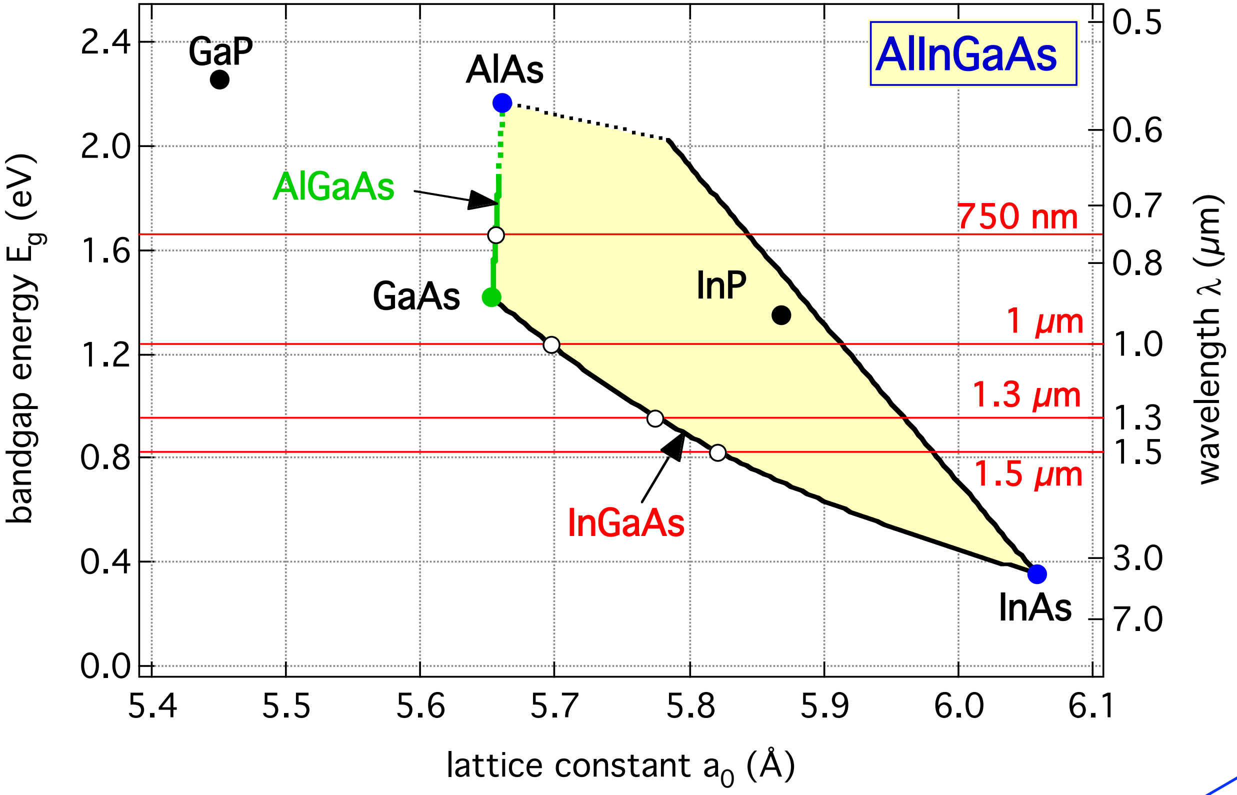
t modes of operation of a laser with a saturable absorber.
; typically occurs with much longer pulses and lower pulse
han CW mode-locking.

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

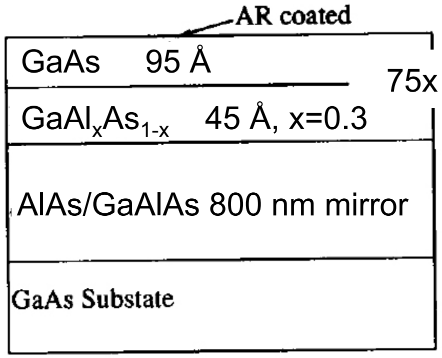
Introduction of the ackronym: SESAM
Invited review article
September 1996, IEEE JSTQE

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

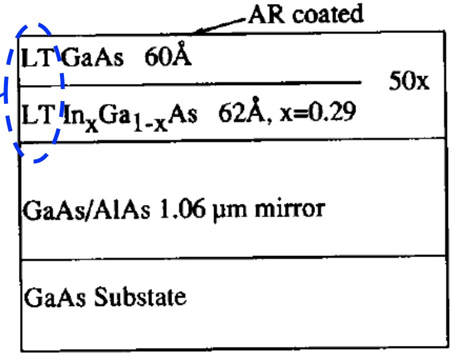
was not trivial .... why?



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

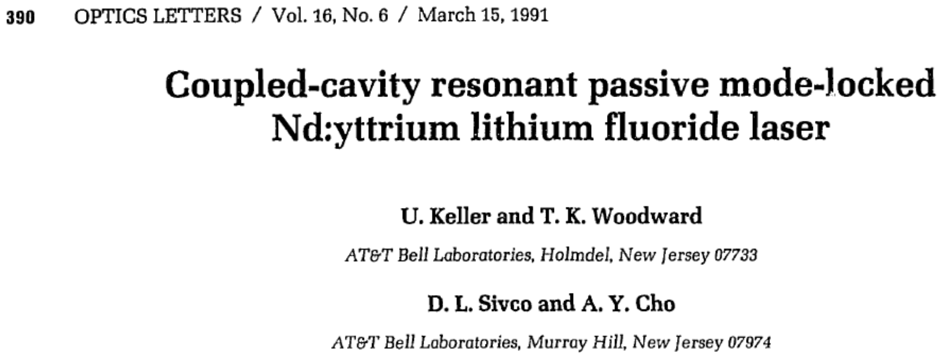


Nd:YLF laser
@ 1.064 μm
IEEE JQE **28**, 1710, 1992



LT = low temperature
MBE growth

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



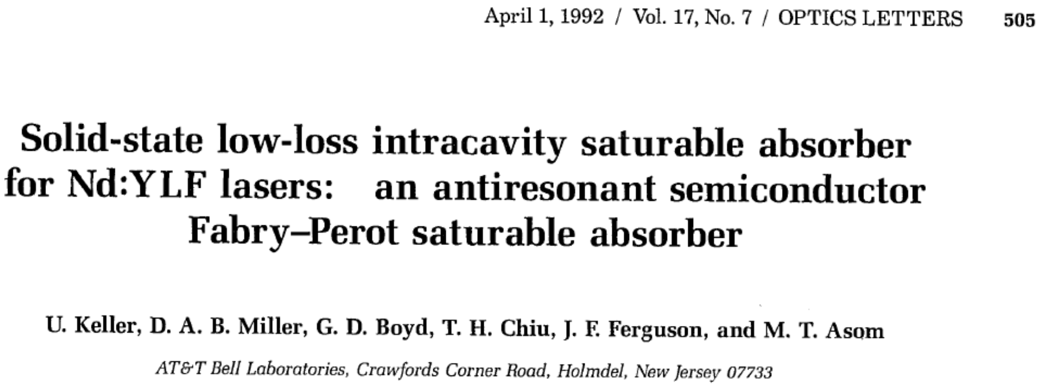
390 OPTICS LETTERS / Vol. 16, No. 6 / March 15, 1991

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

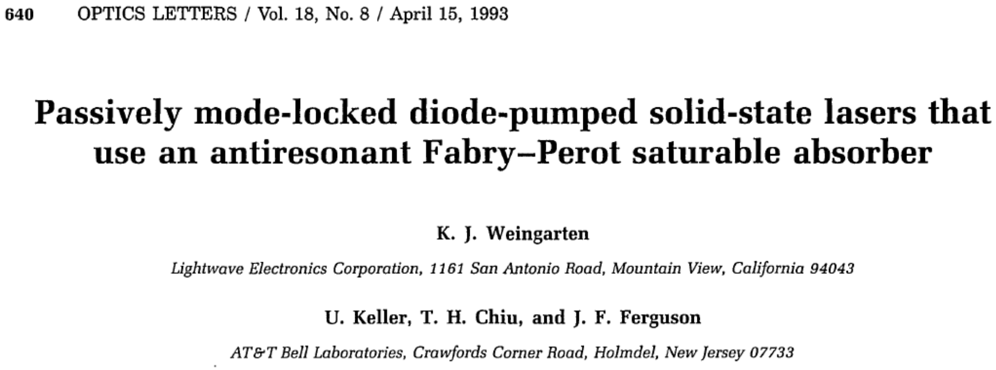
Solid-state low-loss intracavity saturable absorber for Nd:YLF lasers: an antiresonant semiconductor Fabry–Perot saturable absorber

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

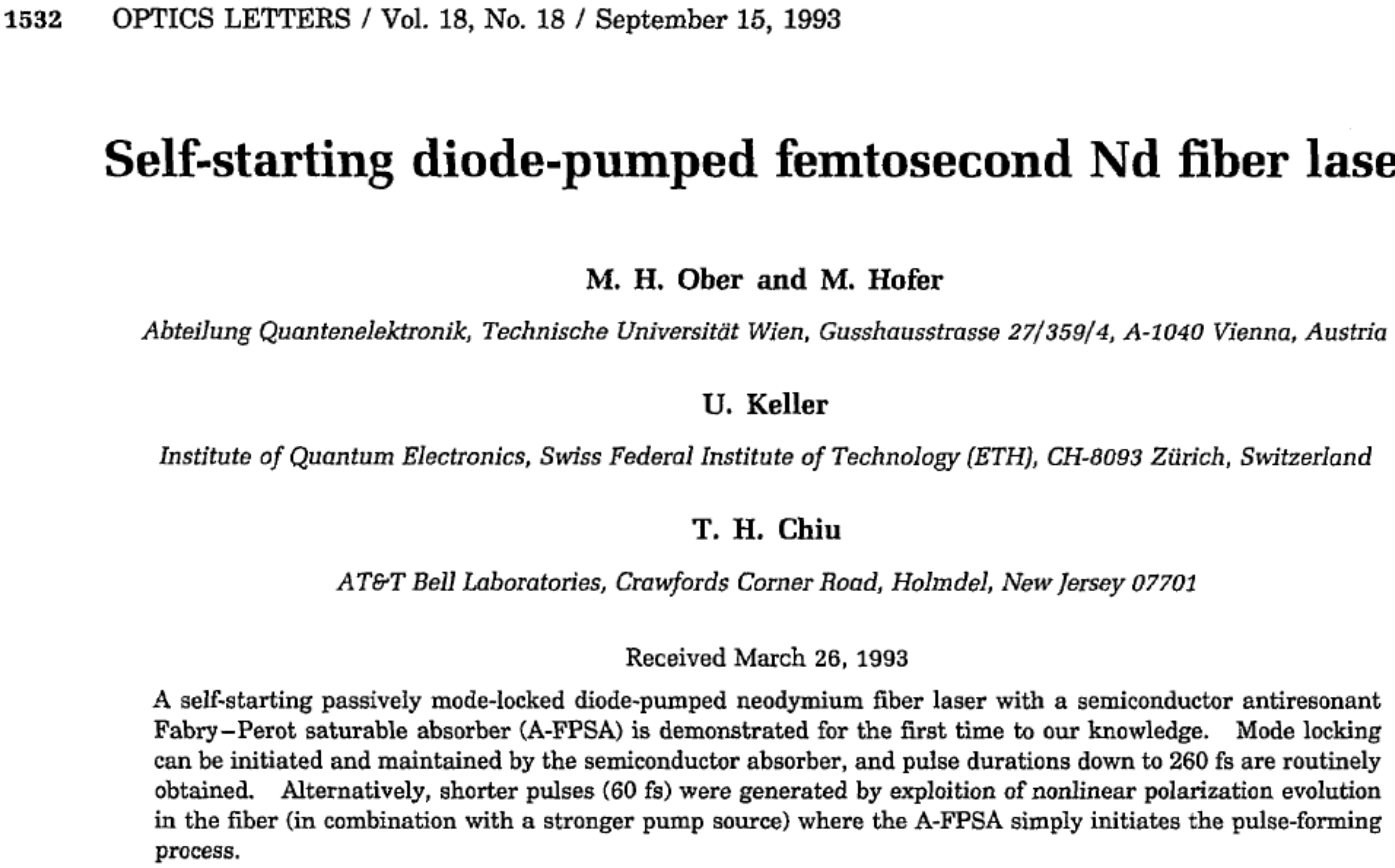
1993

“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

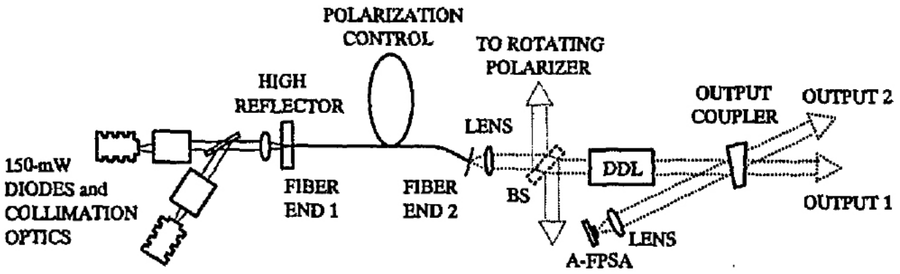
Institute of Quantum Electronics, Swiss Federal Institute of Technology (ETH), CH-8093 Zürich, Switzerland

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 exploition 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”

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.

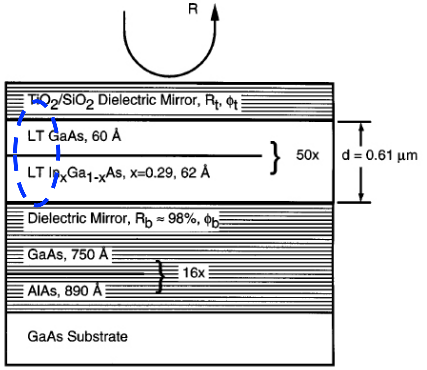


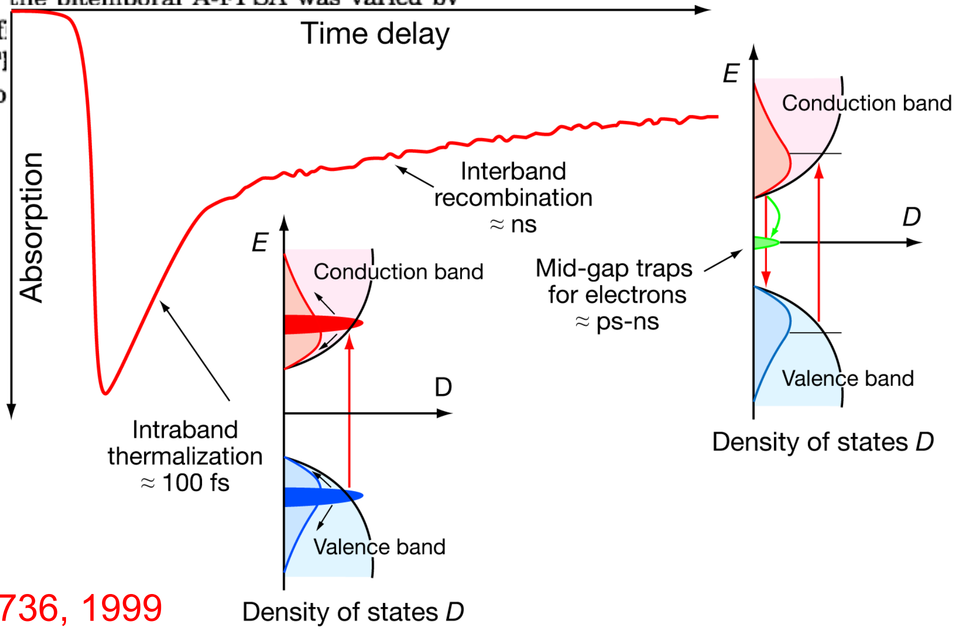
Fig. 1. Structure of an A-FPSA designed for an operation wavelength of ≈1 μm.

Adjustable parameter:
absorber recovery time

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

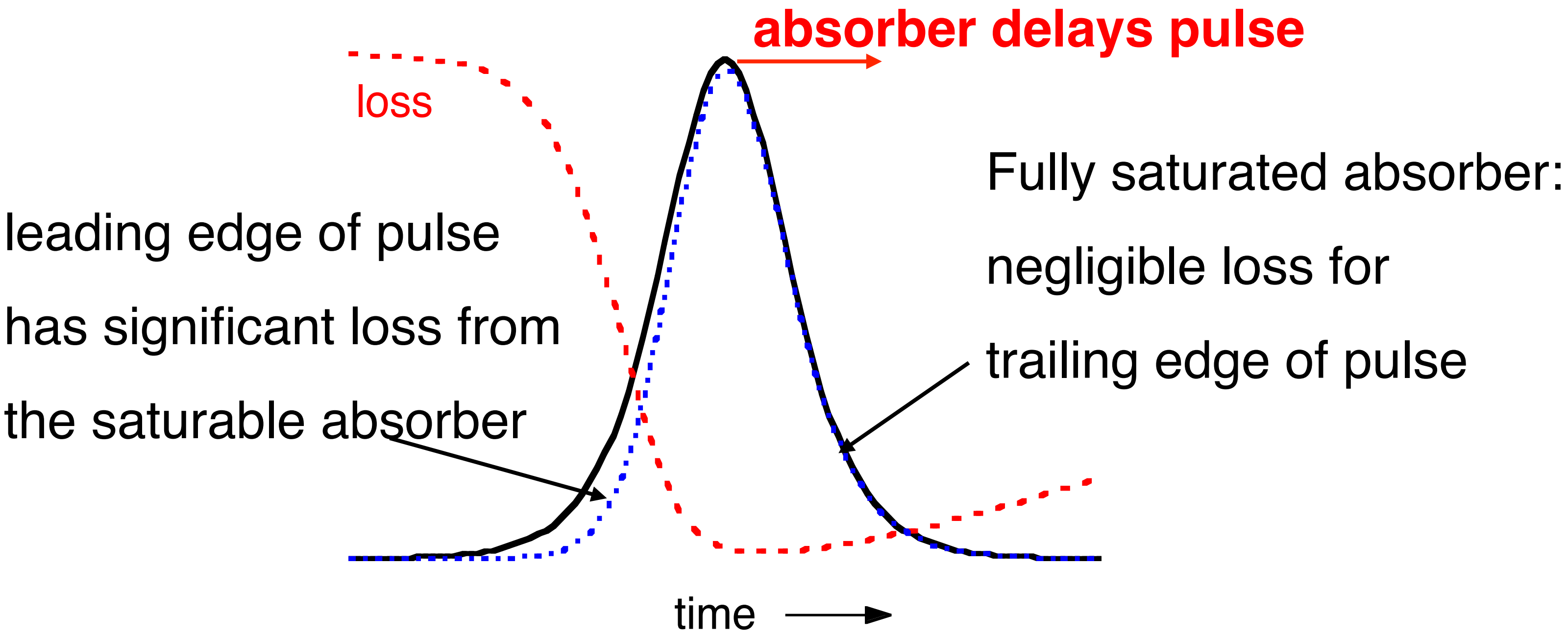
Appl. Phys. Lett., vol. 75, pp. 1437-1439, 1999
Appl. Phys. Lett., vol. 74, pp. 1993-1995, 1999

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



Stable pulses even with a “long” net gain window

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



absorber delays pulse

loss

leading edge of pulse

has significant loss from

the saturable absorber

Fully saturated absorber:

negligible loss for

trailing edge of pulse

time ⟶

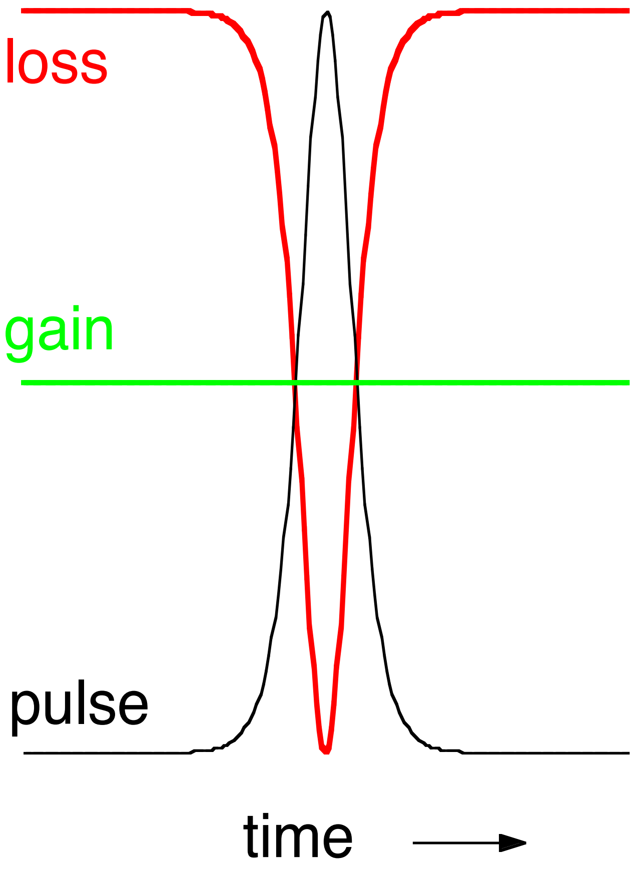
Dominant stabilization process with a relatively long net-gain window:

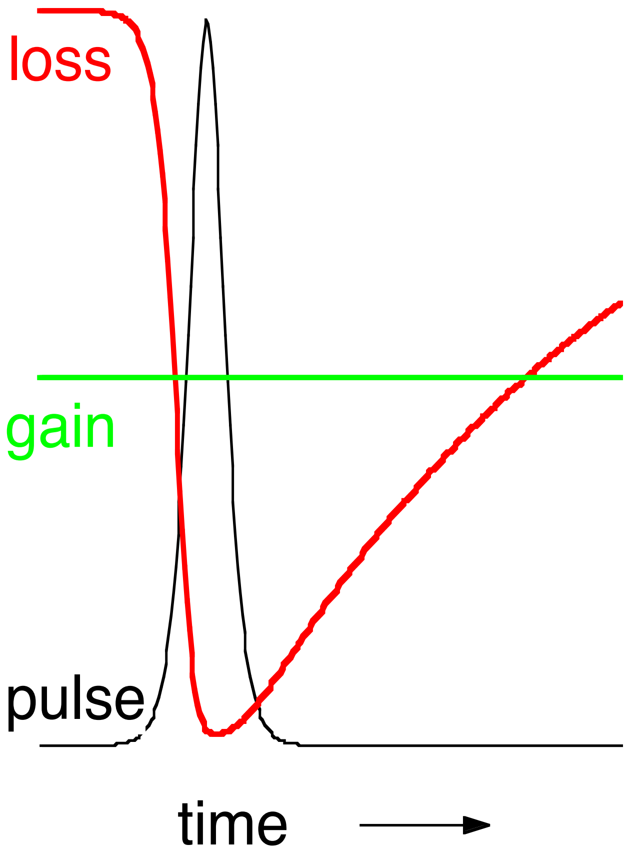
Picosecond domain: absorber delays pulse

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

Femtosecond domain: dispersion in soliton modelocking

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

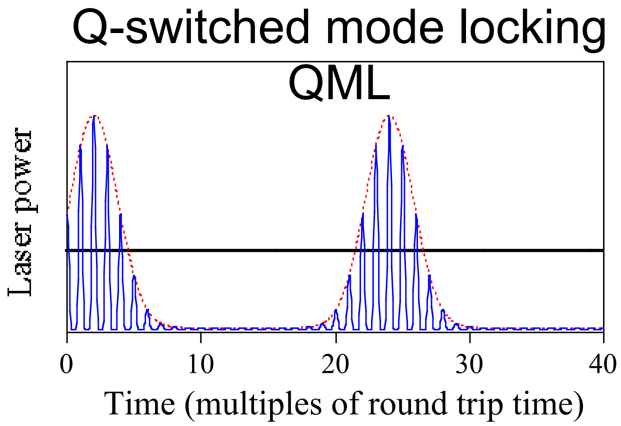
F. X. Kärtner, U. Keller,
Opt. Lett. **20**, 16, 1995

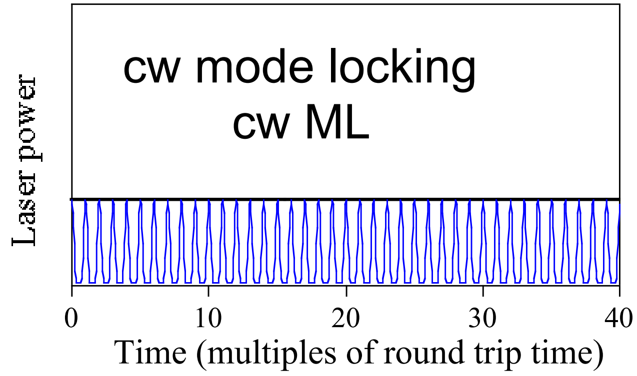
Q-switched mode locking is avoided if...

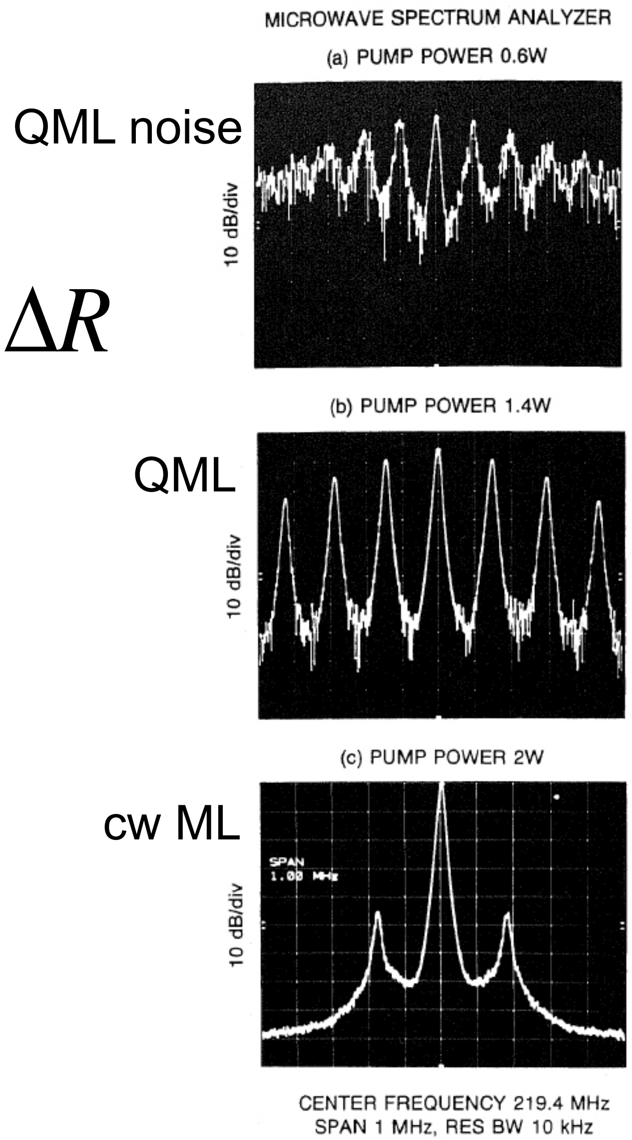
C. Hönninger, R. Paschotta, F. Morier-Genoud, M. Moser, and U. Keller,
JOSA B **16**, 46 (1999)

$$E_P^2 > E_{\mathrm{sat,L}} E_{\mathrm{sat,A}} \Delta R$$

$$= A_{\mathrm{eff,A}} F_{\mathrm{sat,A}} \Delta R$$



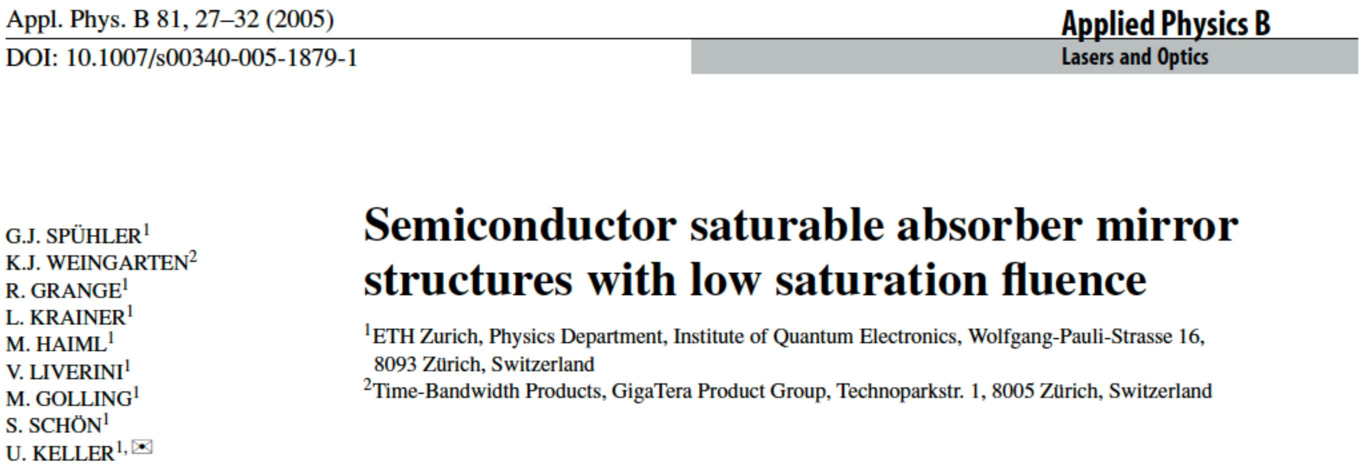




Appl. Phys. B **58**, 347, 1994

SESAMs to reduce Q-switching instabilities

2005 1) SESAMs with low saturation fluence:



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

G.J. SPÜHLER[1]
K.J. WEINGARTEN[2]
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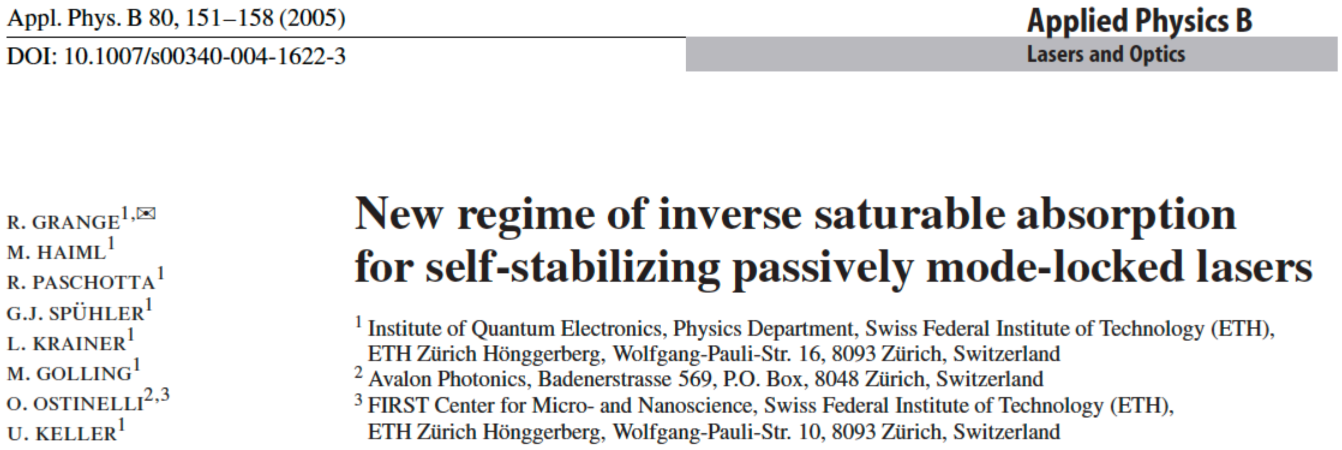
L. KRAINER[1]
M. HAIML[1]
V. LIVERINI[1]
M. GOLLING[1]
S. SCHÖN[1]
U. KELLER[1,✉]

Semiconductor saturable absorber mirror structures with low saturation fluence

[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

2) SESAMs with inverse saturable absorption:



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

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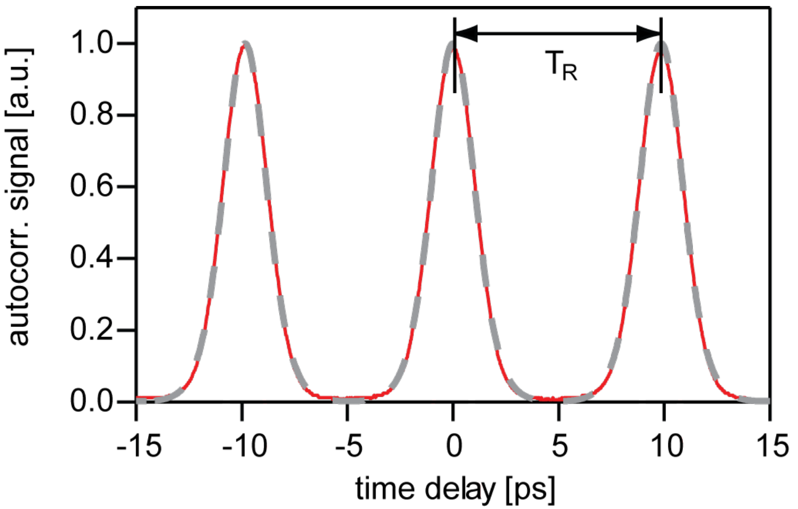
O. OSTINELLI[2,3]
U. KELLER[1]

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

[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

All-optical 100-GHz pulse generation at 1.5 µm

Autocorrelation



Optical spectrum

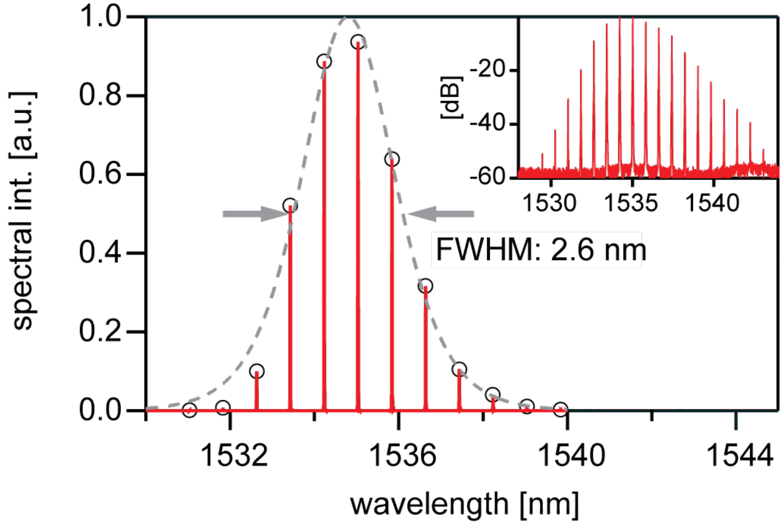
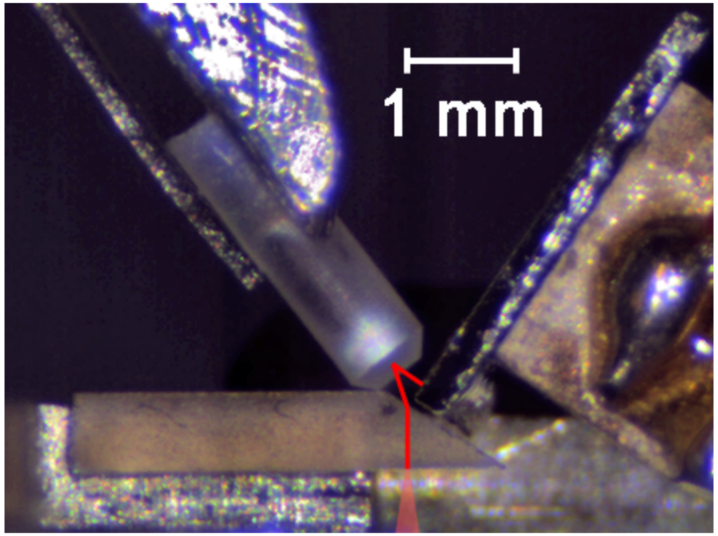


Photo of actual setup



Pulse repetition rate: 101 GHz

Max. output-power: 35 mW

Optical bandwidth: 2.6 nm

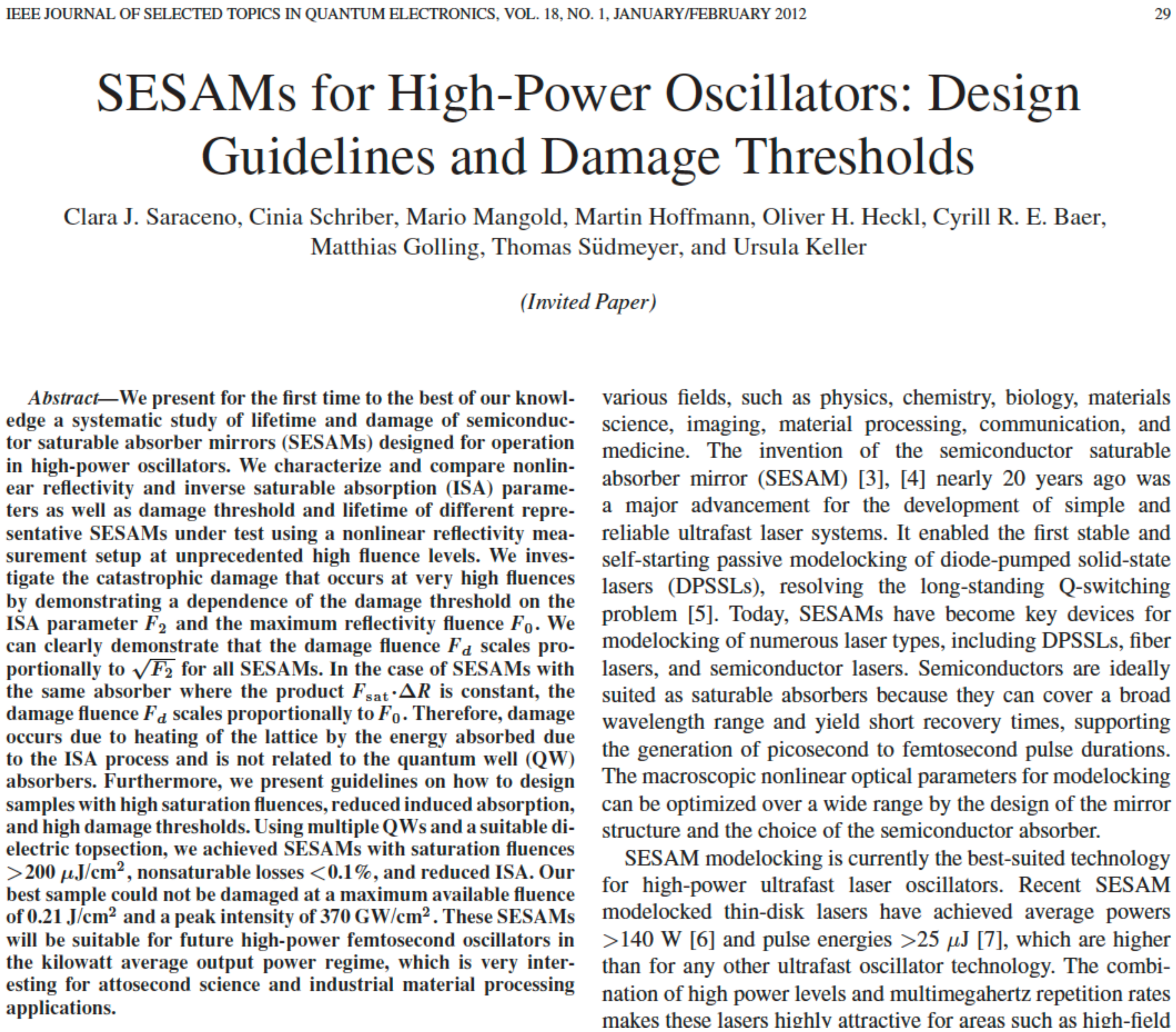
Pulse width: 1.6 ps

(1.7x time-bandwidth limit)

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

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

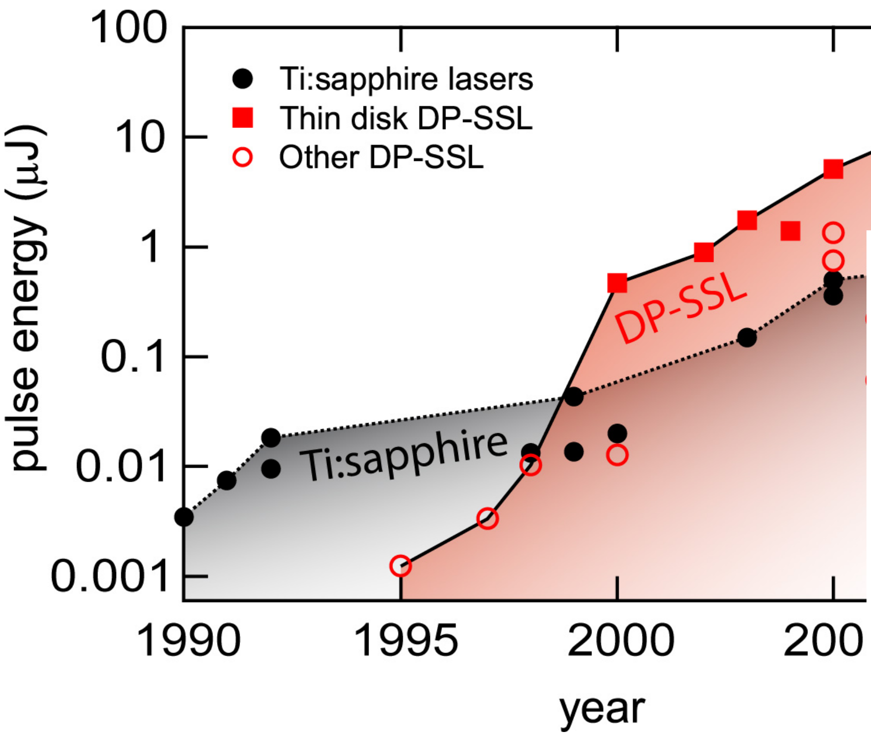
(Invited Paper)

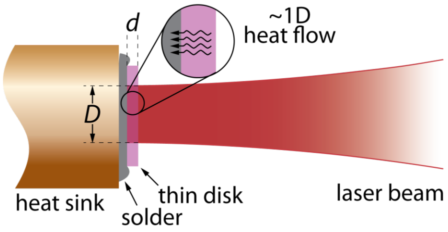
***Abstract*—We present for the first time to the best of our knowledge a systematic study of lifetime and damage of semiconductor saturable absorber mirrors (SESAMs) designed for operation in high-power oscillators. We characterize and compare nonlinear reflectivity and inverse saturable absorption (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 $F_{\mathrm{sat}} \cdot \Delta R$ 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 $>200\ \mu\mathrm{J/cm}^2$, nonsaturable losses $<0.1\%$, and reduced ISA. Our best sample could not be damaged at a maximum available fluence of $0.21\ \mathrm{J/cm}^2$ and a peak intensity of $370\ \mathrm{GW/cm}^2$. 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.**

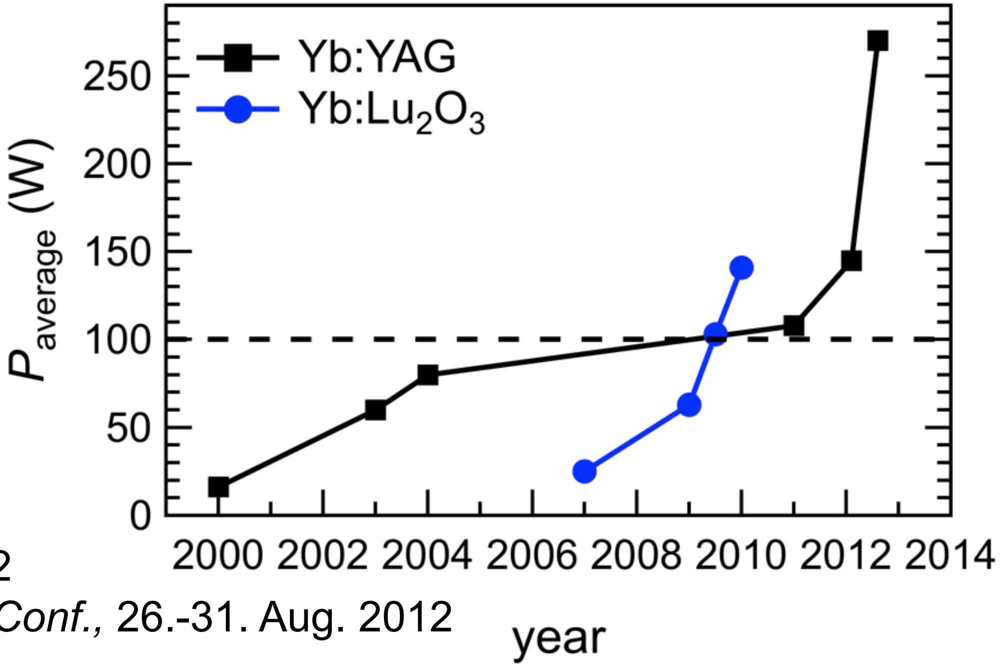
various fields, such as physics, chemistry, biology, materials science, imaging, material processing, communication, and medicine. The invention of the semiconductor saturable absorber mirror (SESAM) [3], [4] nearly 20 years ago was a major advancement for the development of simple and reliable ultrafast 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







C. J. Saraceno et al.,
Opt. Express submitted Aug. 2012
Postdeadline Paper, *Europhoton Conf.,* 26.-31. Aug. 2012

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

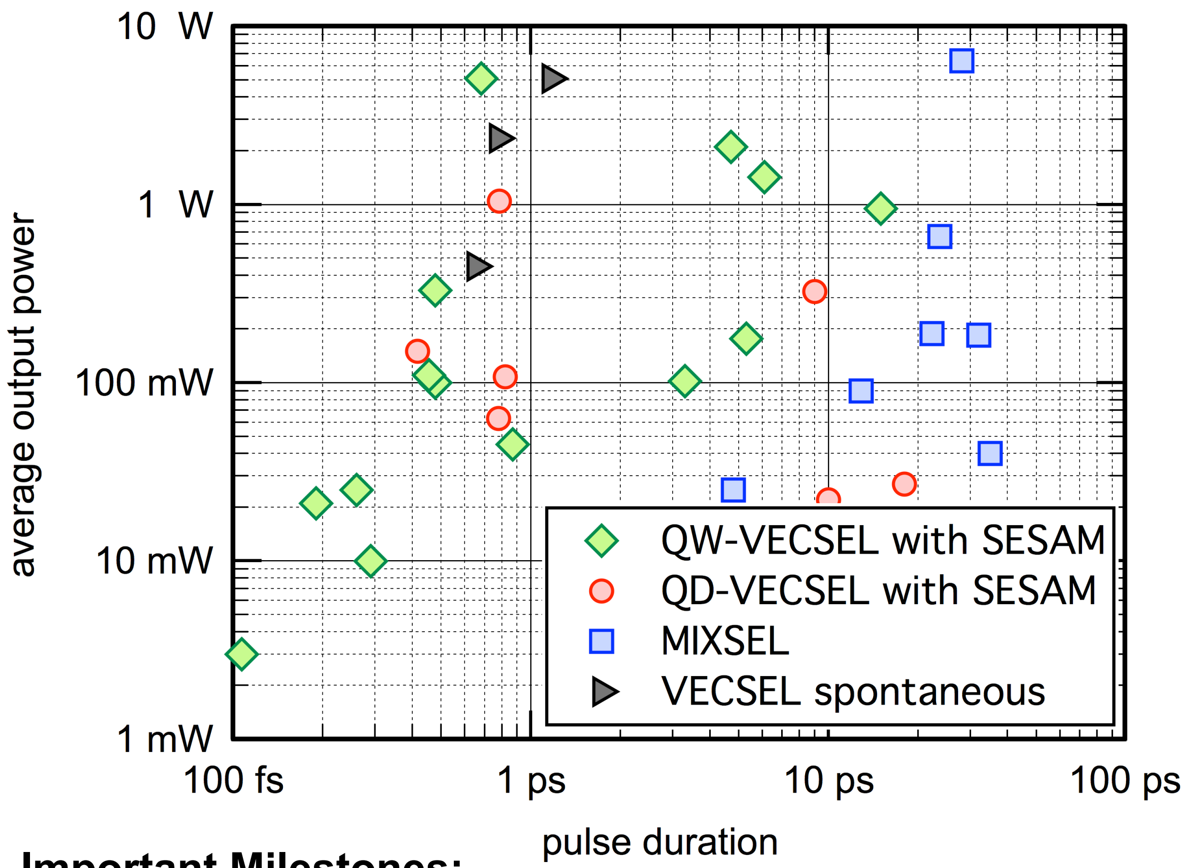
26 µJ with a multipass gain cavity and larger output coupling of 70% (Trumpf/Konstanz)
Opt. Express **16**, 20530, 2008

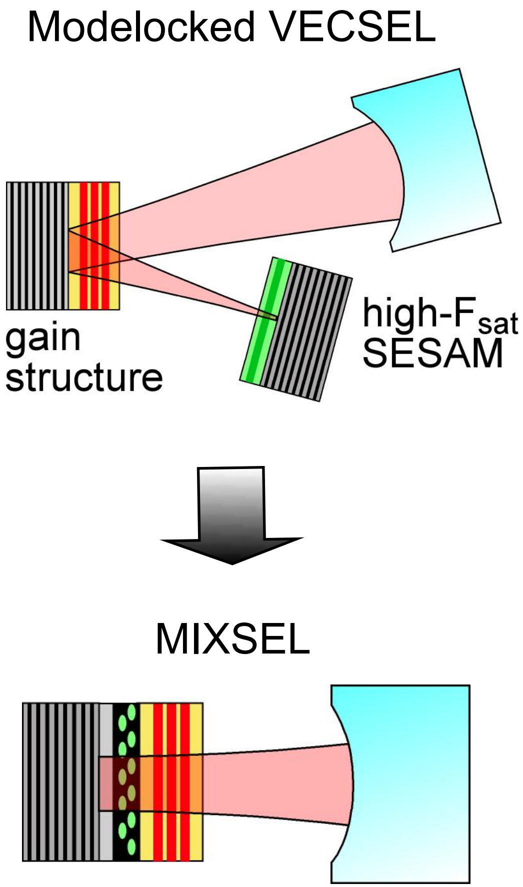
Moving from ss-lasers to semiconductor lasers

Vertical **e**xternal **c**avity **s**urface **e**mitting **l**aser (VECSEL)

Modelocked **i**ntegrated **ex**ternal-cavity **s**urface **e**mitting **l**aser (MIXSEL)

Appl. Phys. B, vol. 88, Nr. 4, pp. 493-497, 2007





Important Milestones:

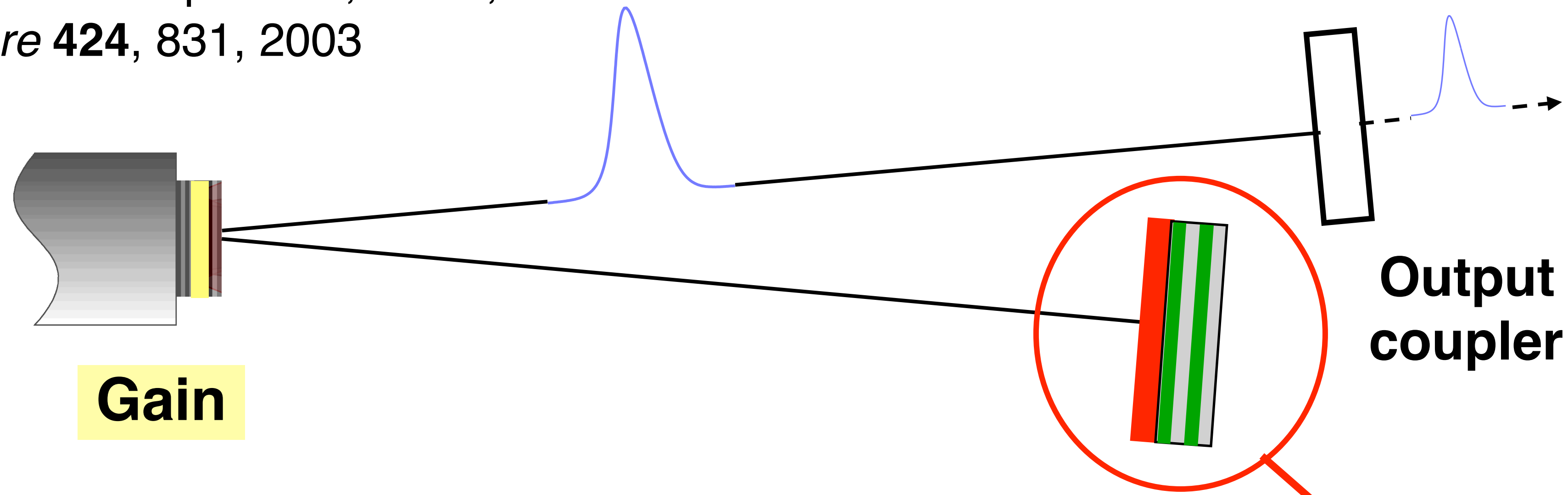
MIXSEL with 6.4 W average output power: *Opt. Express* **18**, 27582, 2010

femtosecond VECSEL with > 1 W average output power: *Opt. Express* **19**, 8108, 2011

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

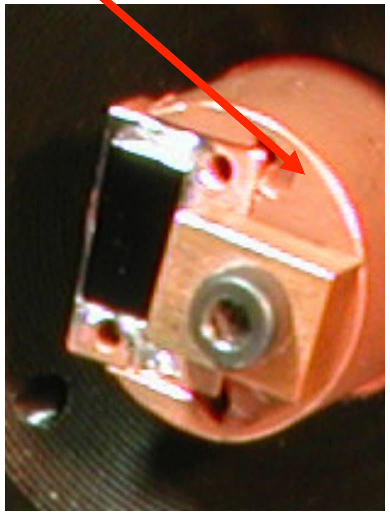
SESAM solved Q-switching problem for diode-pumped solid-state lasers



SESAM

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

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



Thank you to Stanford, Bell Labs and ETH Zurich

Stanford University	**Bell Labs, Holmdel**	**ETH Zurich**
Ph.D. student	MTS	tenured Professor in Physics
1985-1989	1989-1993	since 1993
laser physics ultrafast measurement techniques microwave measurement tools	+ access to state-of-the-art semiconductor materials (MBE)	+ resources to be fully empowered

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

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/paper
- SESAM milestones: http://www.ulp.ethz.ch/research/Sesam
- Ultrafast solid-state laser: get started with the book chapter ... http://www.ulp.ethz.ch/research/UltrafastSolidStateLasers
- VECSEL and MIXSEL: http://www.ulp.ethz.ch/research/VecselMixsel
- Frequency combs: http://www.ulp.ethz.ch/research/FrequencyComb
- Attoscience, Attoclock, Attoline:
- http://www.ulp.ethz.ch/research/Attosecondscience
- http://www.ulp.ethz.ch/research/Attoline
- http://www.ulp.ethz.ch/research/Attoclock
- Viewgraphs to graduate lecture course: Ultrafast Laser Physics http://www.ulp.ethz.ch/education/ultrafastlaserphysics/viewgraphs