Fundamentals of frequency combs: What they are and how they work

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KISS Worshop: "Optical Frequency Combs for Space Applications"

Outline

1. **Optical frequency combs in timekeeping**
   - How we got to where we are now….

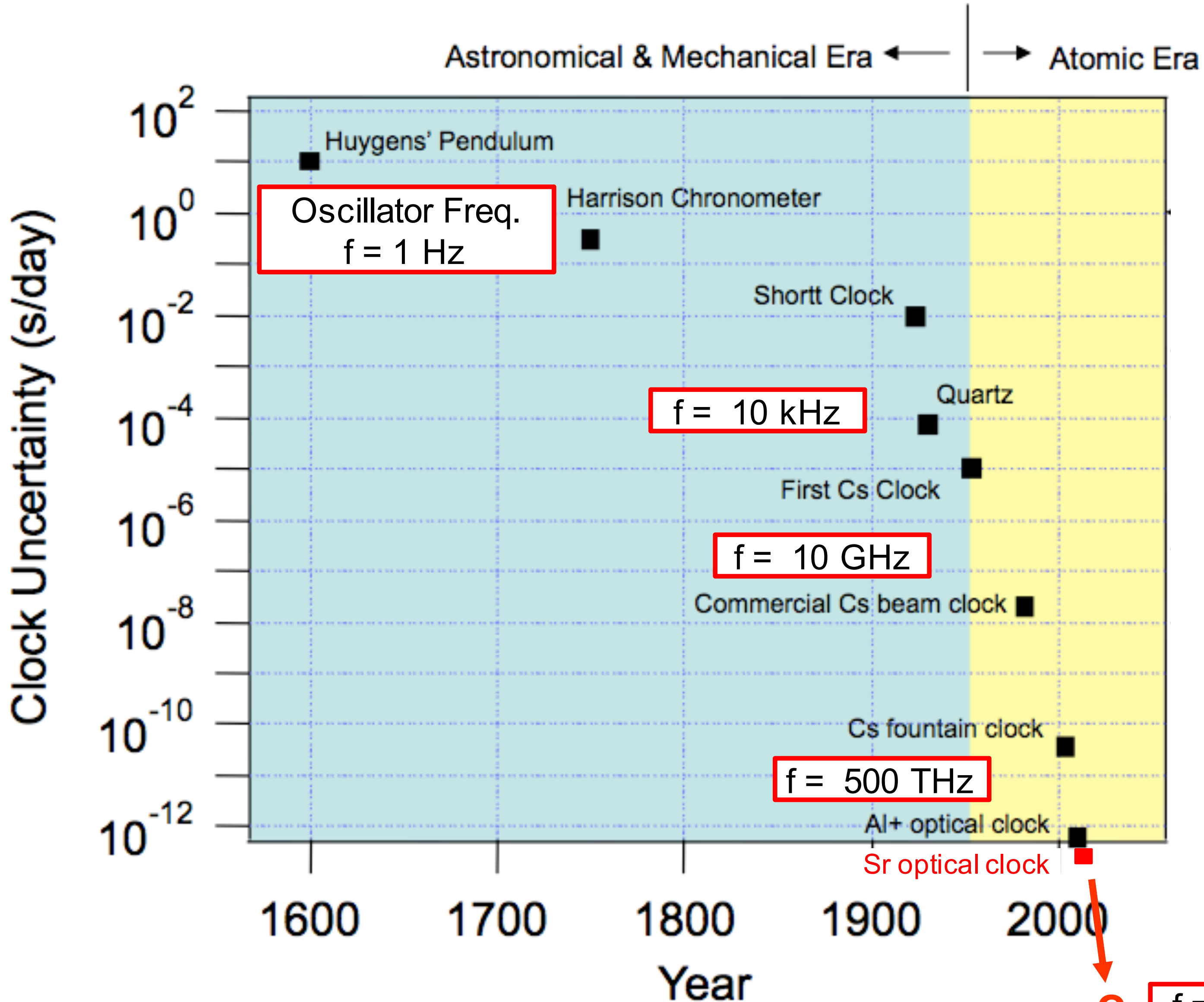
2. **The multiple faces of an optical frequency comb**

3. **Classes of frequency combs and their basic operation principles**
   - Mode-locked lasers
   - Microcombs
   - Electro-optic frequency combs

4. **Challenges and opportunities for frequency combs**

NIST

Timekeeping: The long view



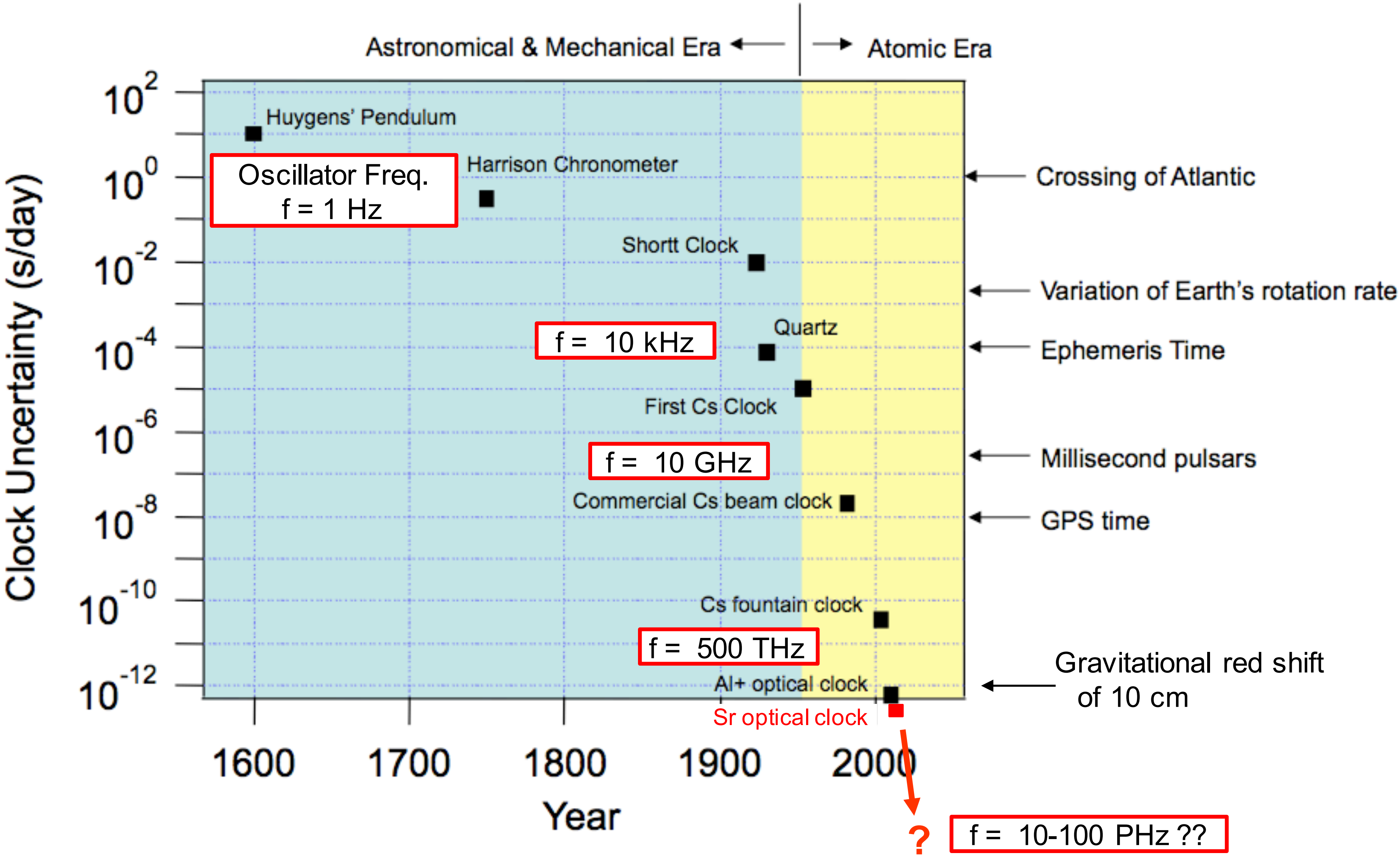
Rate of improvement since 1950:
1.2 decades / 10 years

"Moore's Law":
1.5 decades / 10 years

NIST

S. Diddams, et al, Science (2004)

Timekeeping: The long view



S. Diddams, et al, Science (2004)

Use higher frequencies !

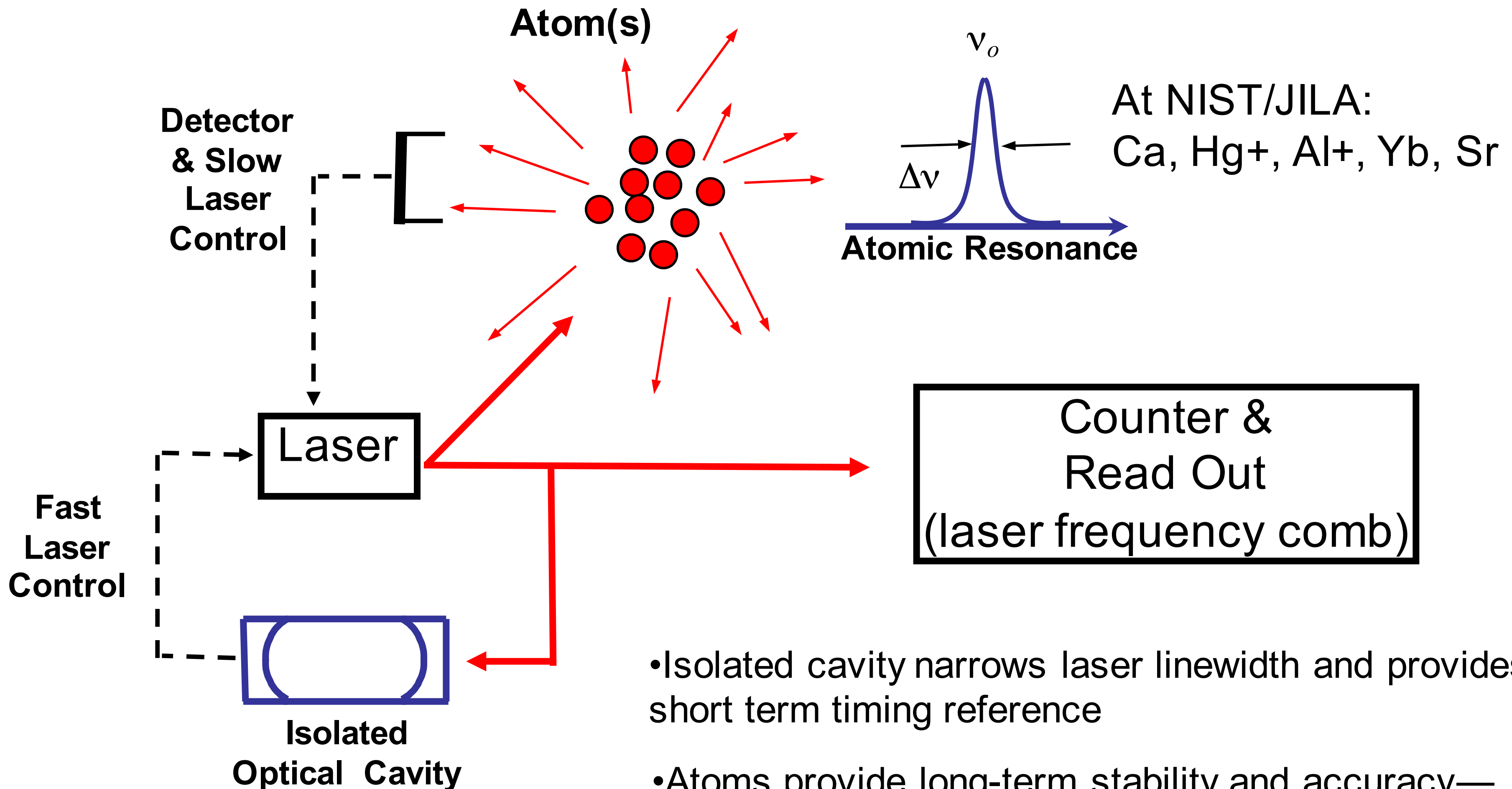
Dividing the second into smaller pieces yields superior frequency standards and metrology tools:

$$\frac{\nu_{\text{optical}}}{\nu_{\text{microwave}}} \approx \frac{10^{15}}{10^{10}} \approx 10^{5}$$

In principle (!), optical standards could surpass their microwave counterparts by up to five orders of magnitude

... but how can one count, control and measure optical frequencies?

Optical Atomic Clocks



- Isolated cavity narrows laser linewidth and provides short term timing reference
- Atoms provide long-term stability and accuracy— **now now at 10^{-18} level!**
- Laser frequency comb acts as a divider/counter

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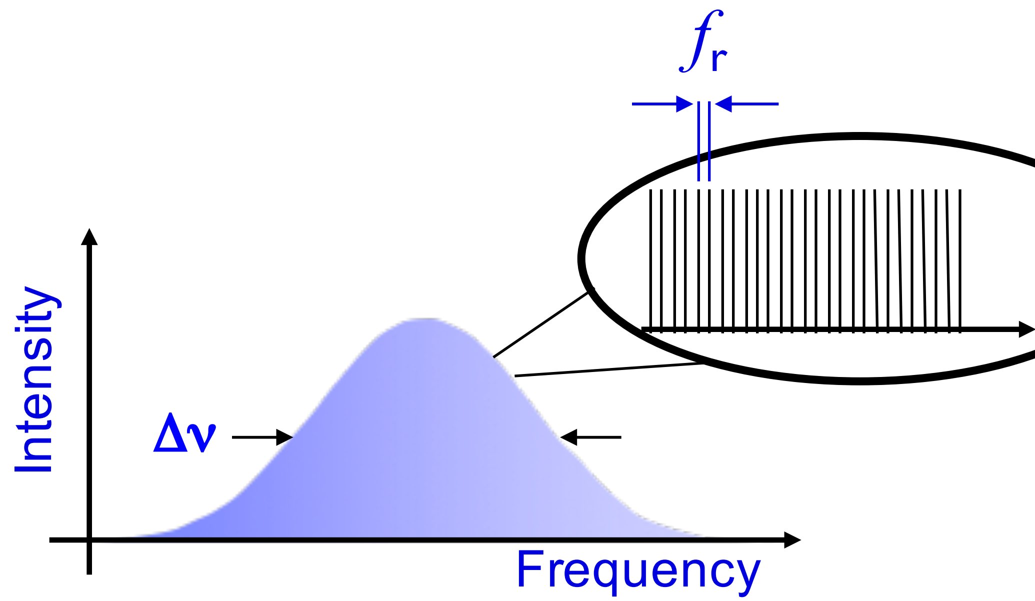
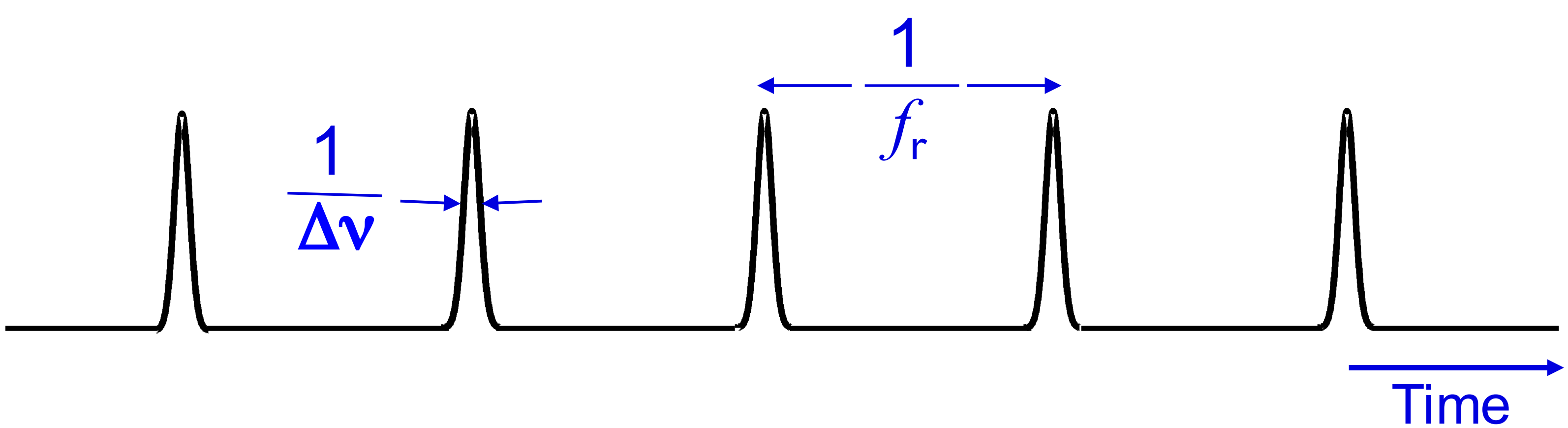
Multiple faces of a frequency comb

1. A ruler for light frequencies

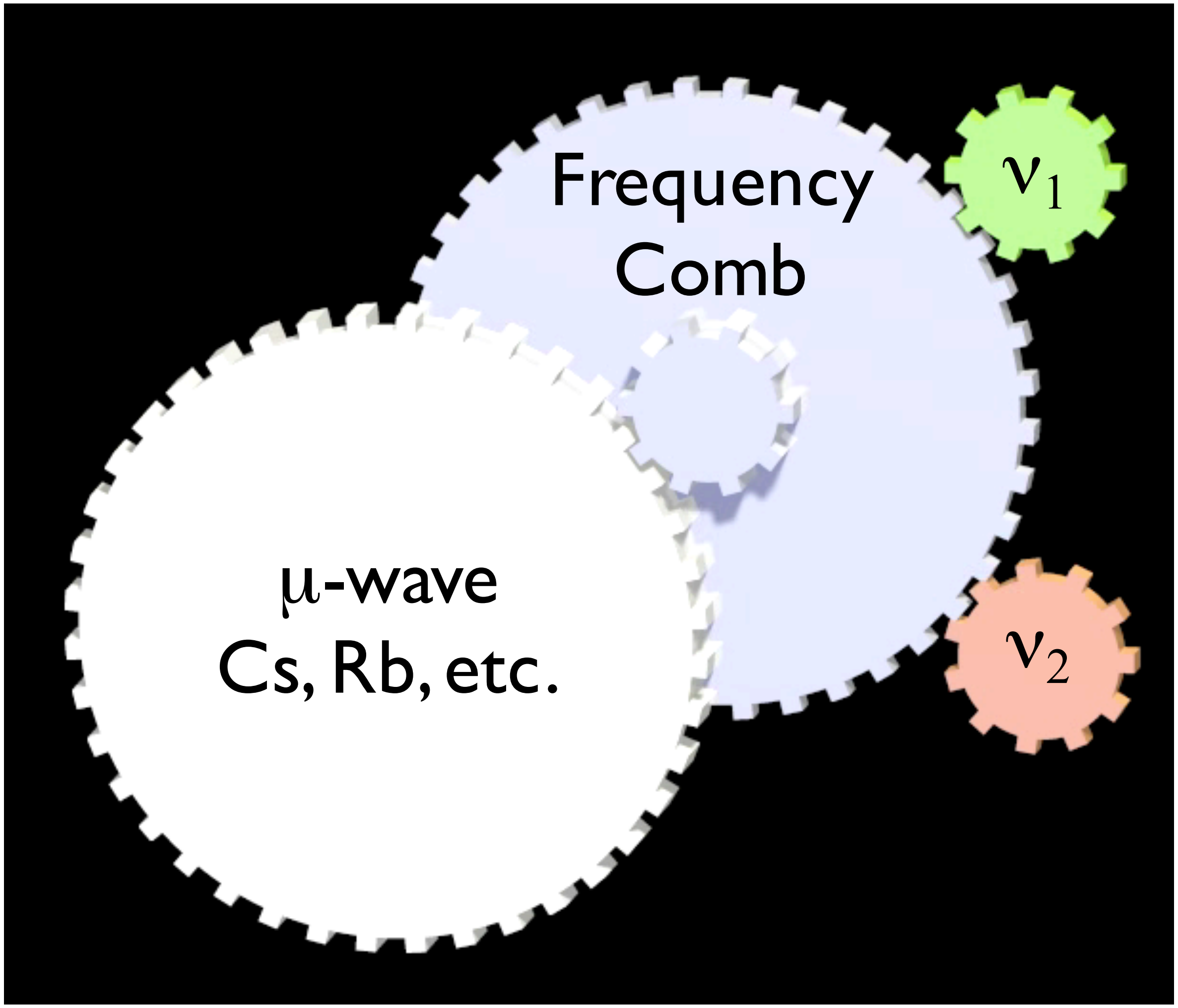


2. A perfectly-spaced train of optical pulses



Multiple faces of a frequency comb

3. An optical clockwork



- Comb uncertainty at the 20th decimal place
- Measurement of optical ratios (e.g. $\nu_1 : \nu_2$)
- Direct connection from optical to microwave domains

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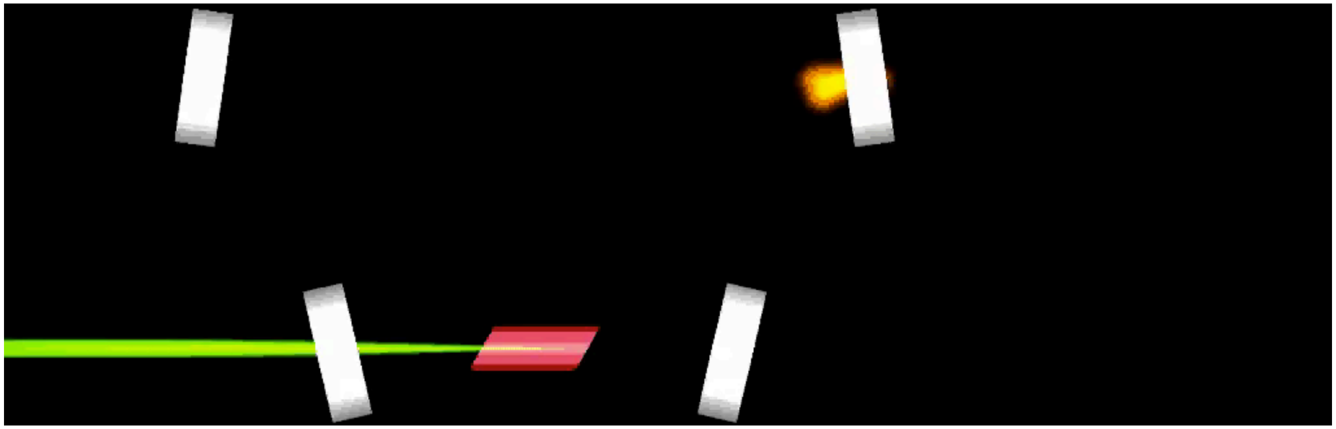
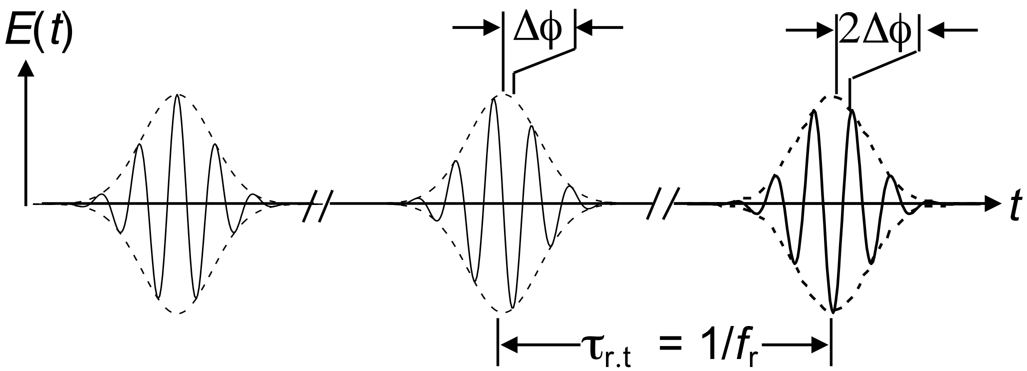
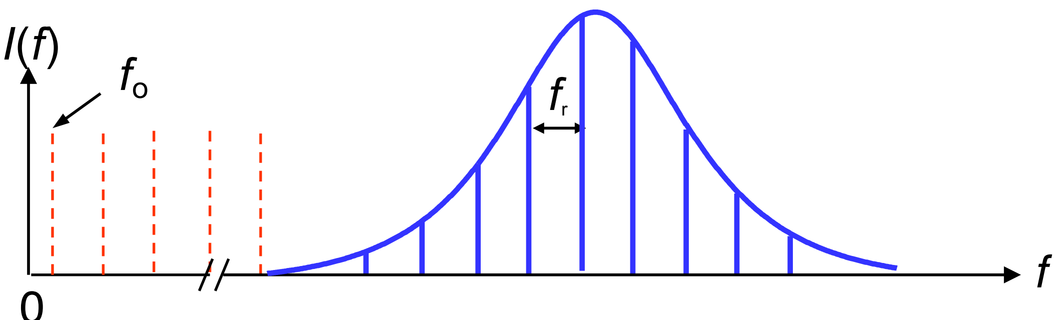
Mode-Locked Laser: Basis of the Frequency Comb



Time domain



Frequency domain



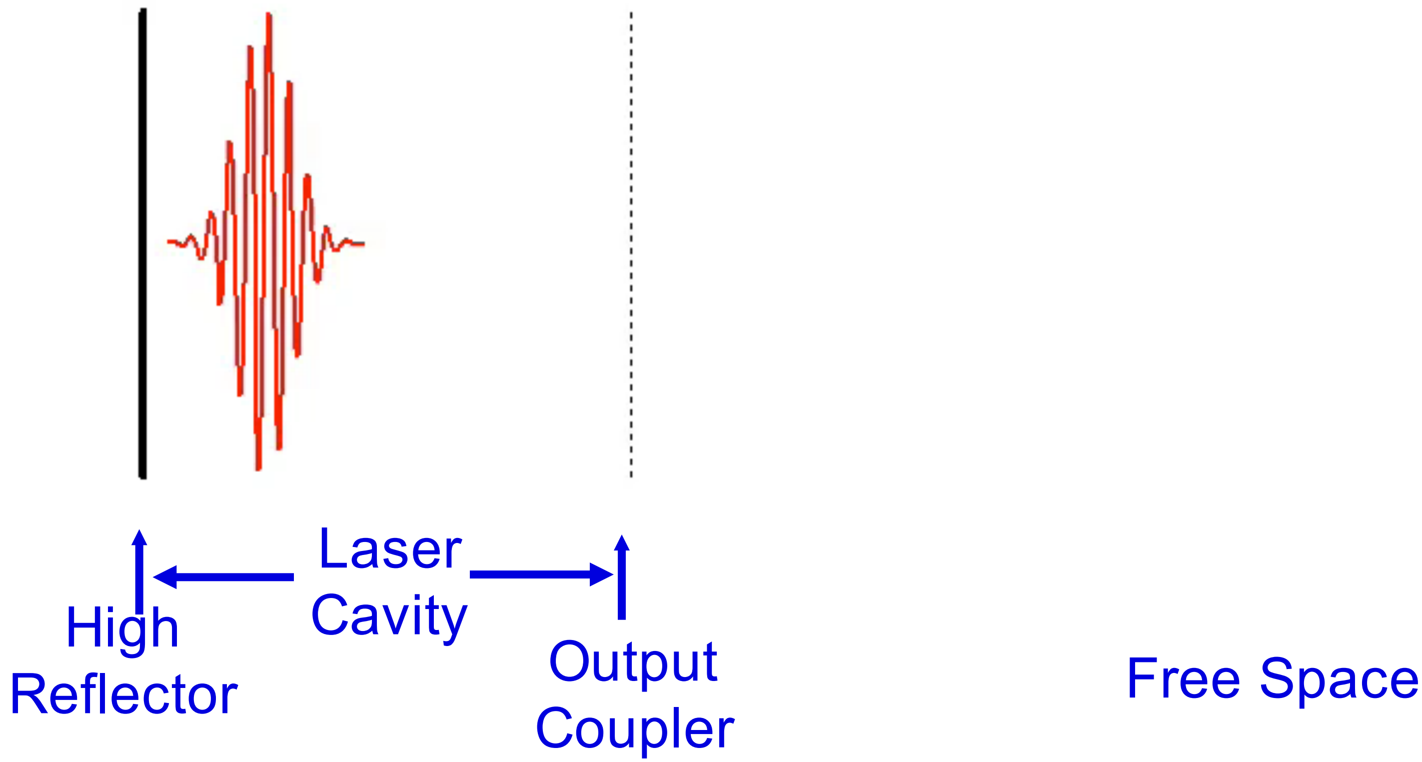
Key Concept:

Direct link between optical and microwave frequencies

$$\nu_n = nf_r + f_o$$

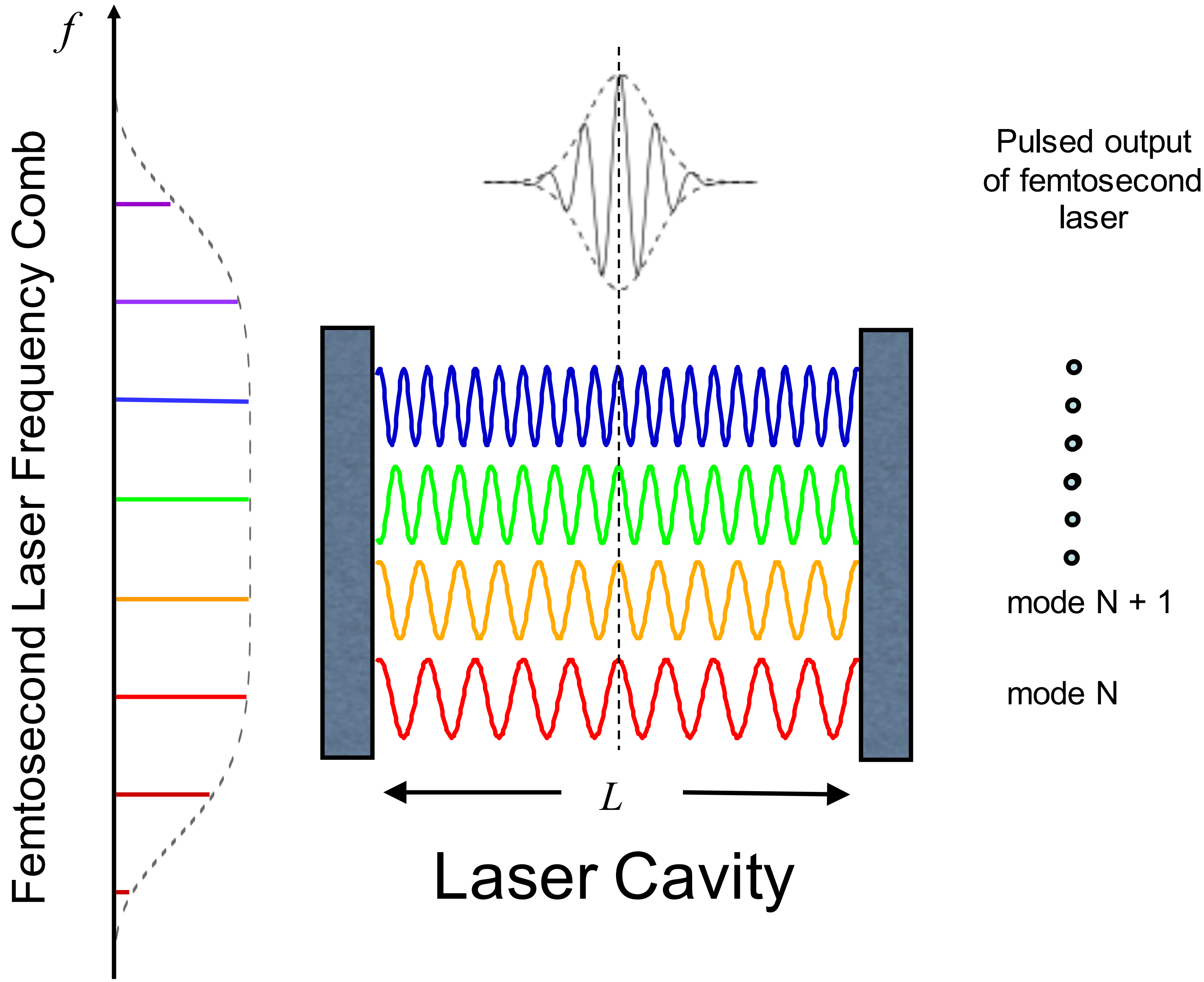
$$n \sim 10^5$$

Group and phase velocity in modelocked lasers



animation from *Steve Cundiff*

The femtosecond mode-locked laser comb



→ Cavity modes are locked in phase to generate a short pulse once every roundtrip time $2L/v_g$

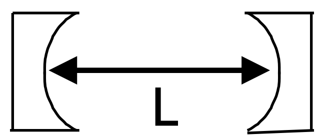
How does it work?

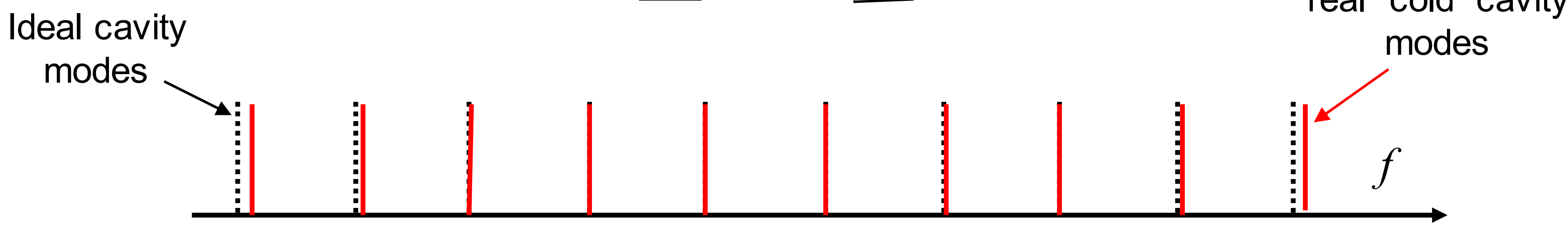
→ All Femtosecond lasers require:

- Laser cavity + broadband gain source and optical components
- **Dispersion control**
- **Power-dependent gain or loss**
- **Phase modulation**

ideal mode spacing:

$$\frac{c}{2L}$$



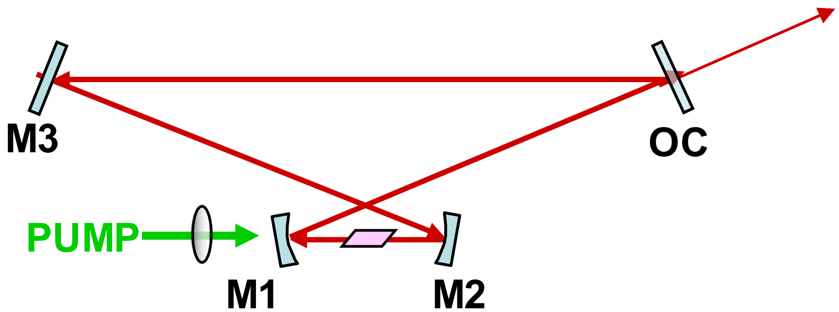


→ Due to dispersion, the cavity modes are not evenly spaced

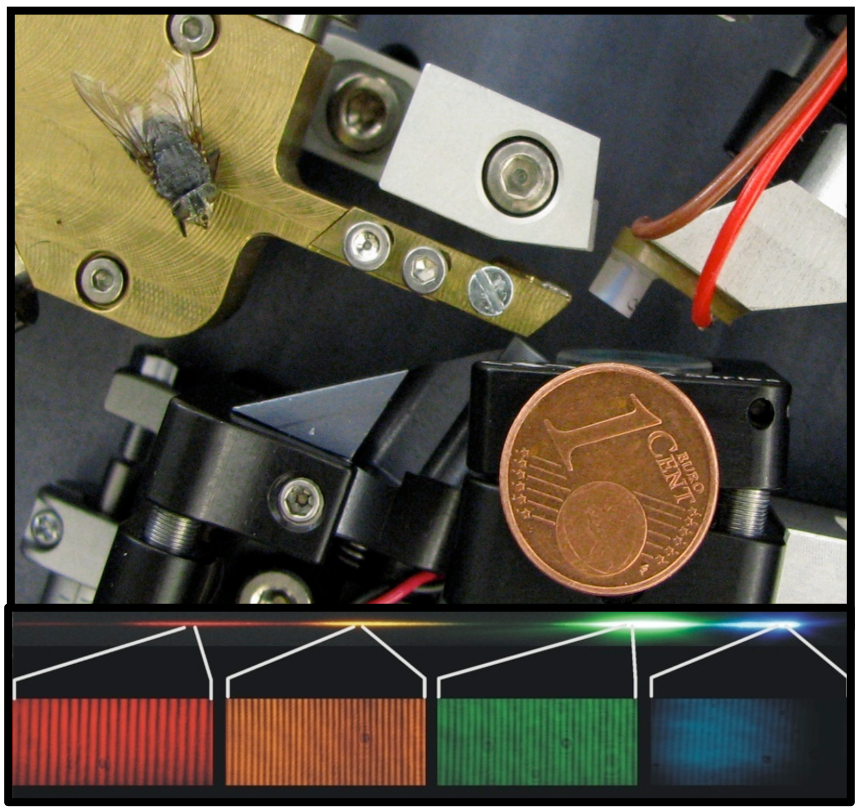
→ However, the **nonlinear phase-modulation** in a mode-locked laser provides the required synchronization of the modes, yielding a strictly uniform mode comb.

GHz Rep Rate Ti:Sapphire Combs

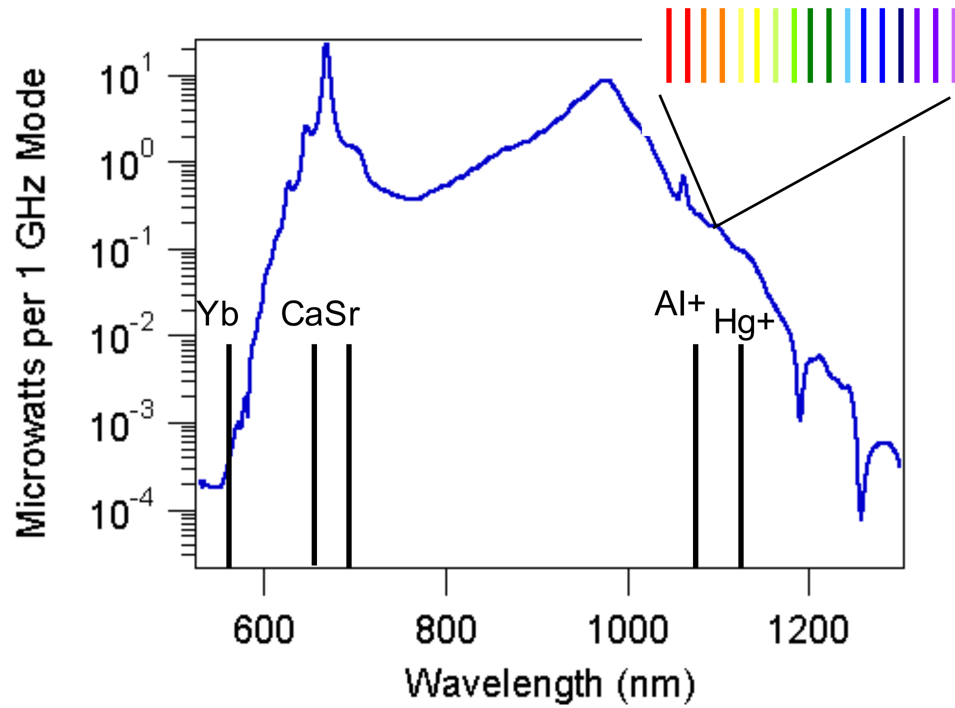
T. Fortier, A. Bartels, D. Heinecke, M. Kirchner



10 GHz Self-referenced Ti:sapphire Laser



1 GHz Octave Spanning Laser



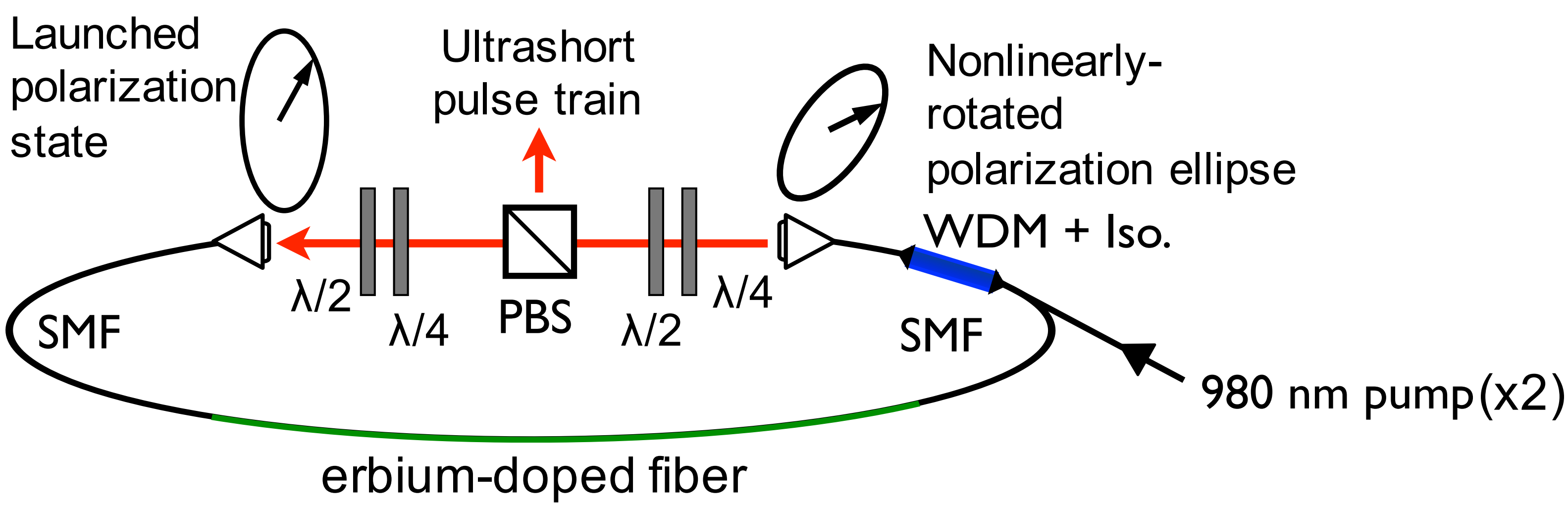
A. Bartels, H Kurz, *Opt. Lett.* 27, 1839 (2002)
T. Fortier, A. Bartels, S. Diddams, *CLEO* (2005)
T. Fortier, A. Bartels, S. Diddams, *Opt. Lett.* 31, 1011 (2006)

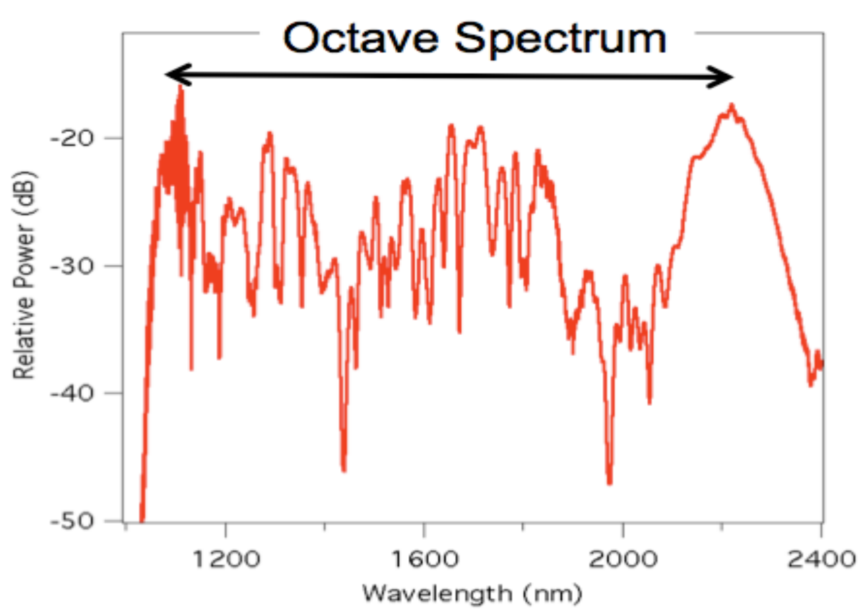
- Stabilized Comb = 10^6 Modes
- Hz-level linewidths
- Residual frequency noise at 1×10^{-19} level

A. Bartels, D. Heinecke, S. Diddams, *Science* **326**, 681 (2009).

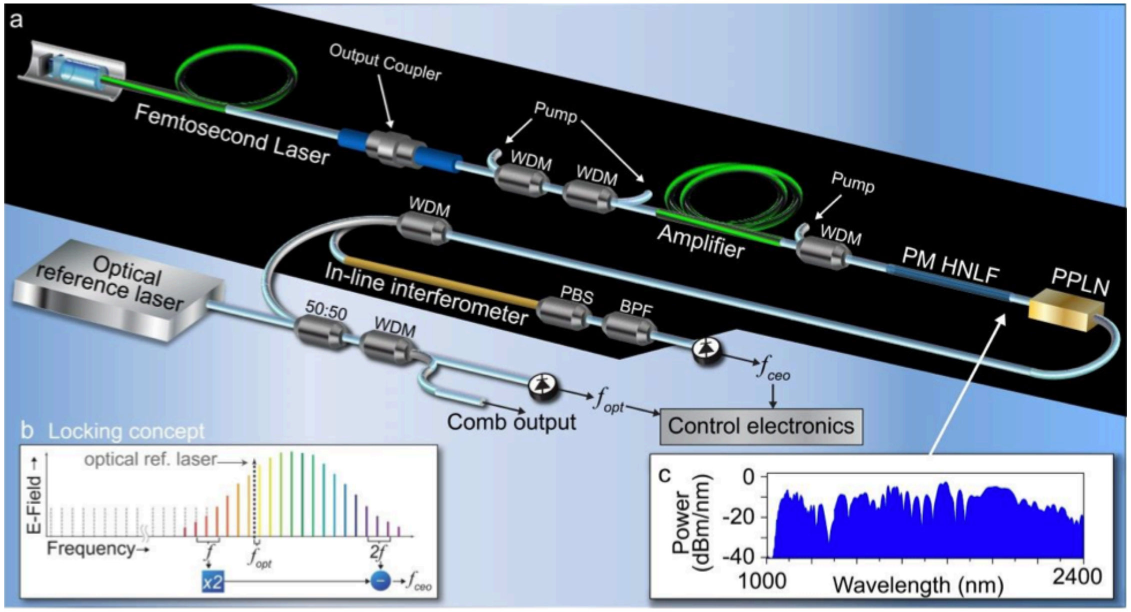
Er:fiber based frequency combs

→ mode-locking based on nonlinear polarization rotation





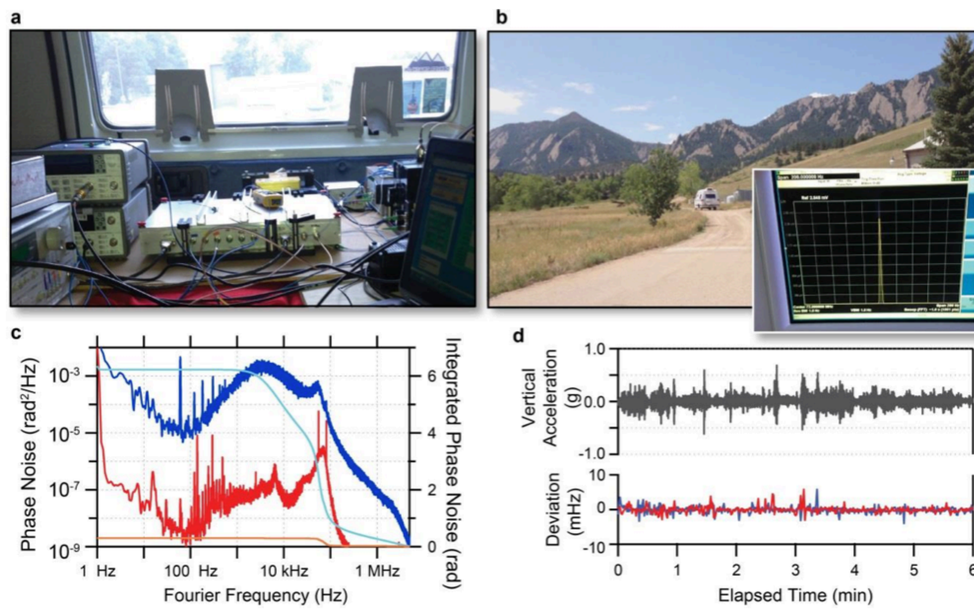
Polarization-maintaining Er:fiber laser comb



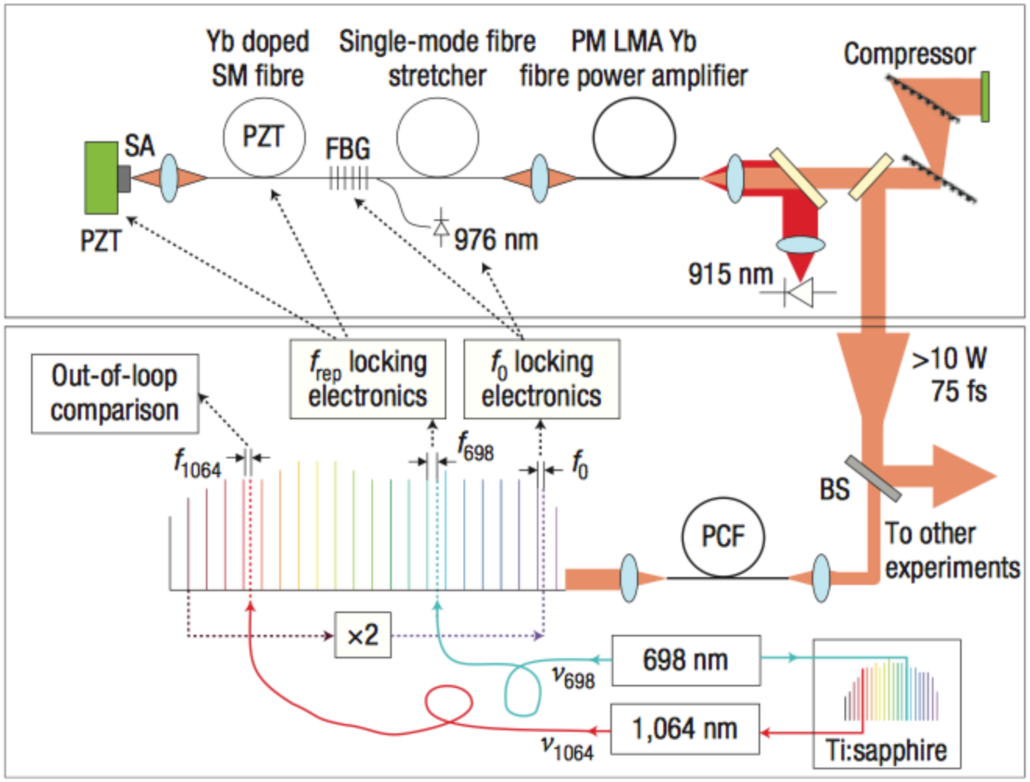
- Laser + amplifier + self-referencing are all constructed "in-line" with polarization-maintaining (PM) fiber optics.
- Laser is mode-locked with saturable absorber mirror
- Robust against environmental perturbations.

(Newbury group at NIST)

Frequency comb operates phase-locked in a moving vehicle.



High-power Yb:fiber laser frequency comb

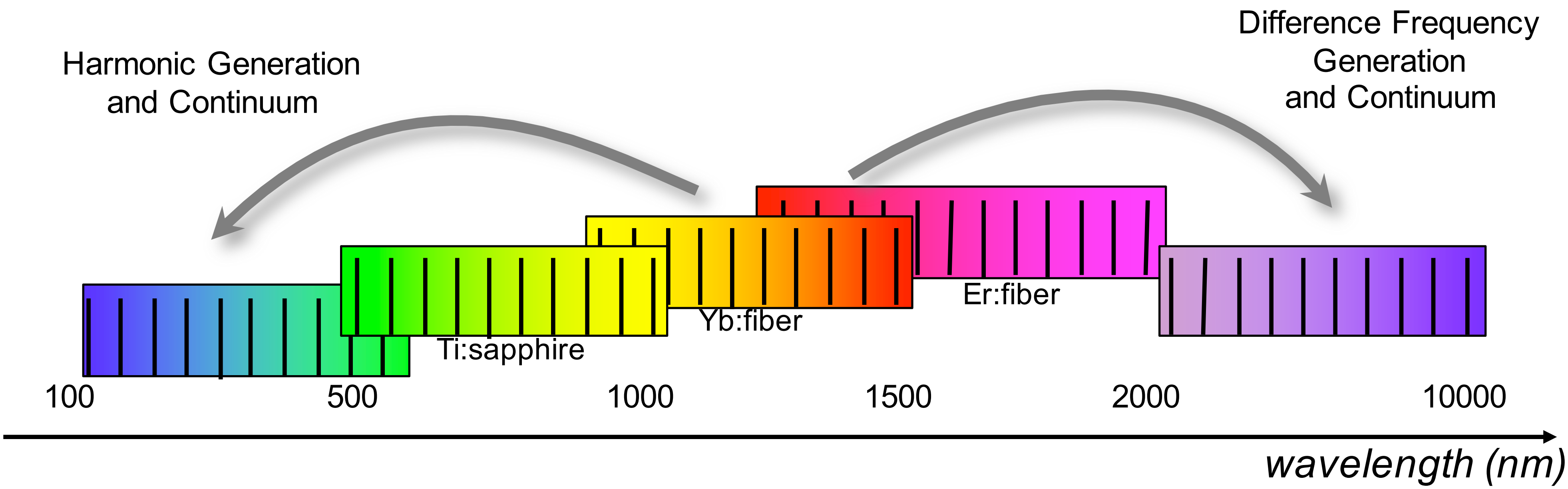


- Linear cavity design
- Saturable absorber end mirror for mode-locking
- Fiber Bragg grating provides output coupling and dispersion control
- **External amplification to ~80 W** followed by compression to ~100 femtosecond pulses

Schibli, et al. *Nature Photonics* **2**, 355 - 359 (2008)

Frequency Comb Extension via Nonlinear Optics

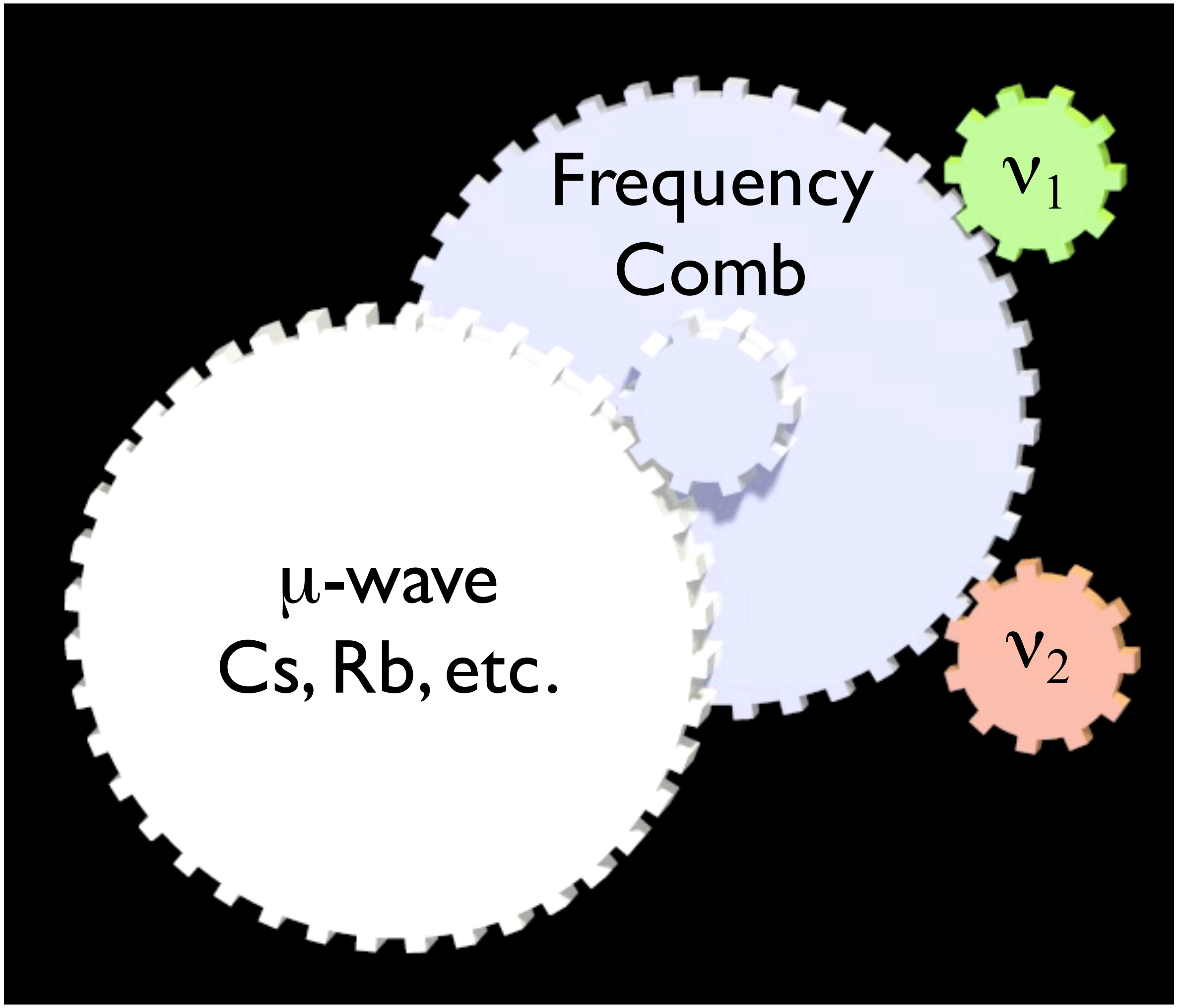
- Using a combination of harmonic generation, difference frequency generation and super-continuum, frequency combs have been extended from the UV to the infrared



- Some examples:
  - Extreme ultraviolet via harmonic generation: *Phys. Rev. Lett*. **94**, 193201 (2005); *Nature* **436**, 234-237 (2005); *Science* **307**, 400 (2005);
  - Mid-infrared comb generation via OPO, DFG and supercontinuum: *Opt. Lett.* **34**, 1330 (2009); *Opt. Lett.* **37**, 1400 (2012); *Lett.* **39**, 2056 (2014); *Opt. Lett*. **36**, 2275-2277 (2011).

Multiple faces of a frequency comb

3. An optical clockwork



- Comb uncertainty at the 20th decimal place
- Measurement of optical ratios (e.g. $\nu_1 : \nu_2$)
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Controlling the femtosecond laser comb

For most applications with the femtosecond laser frequency comb, we need to measure and control the two degrees of freedom of the frequency comb: f_o (offset frequency) and f_r (repetition rate)

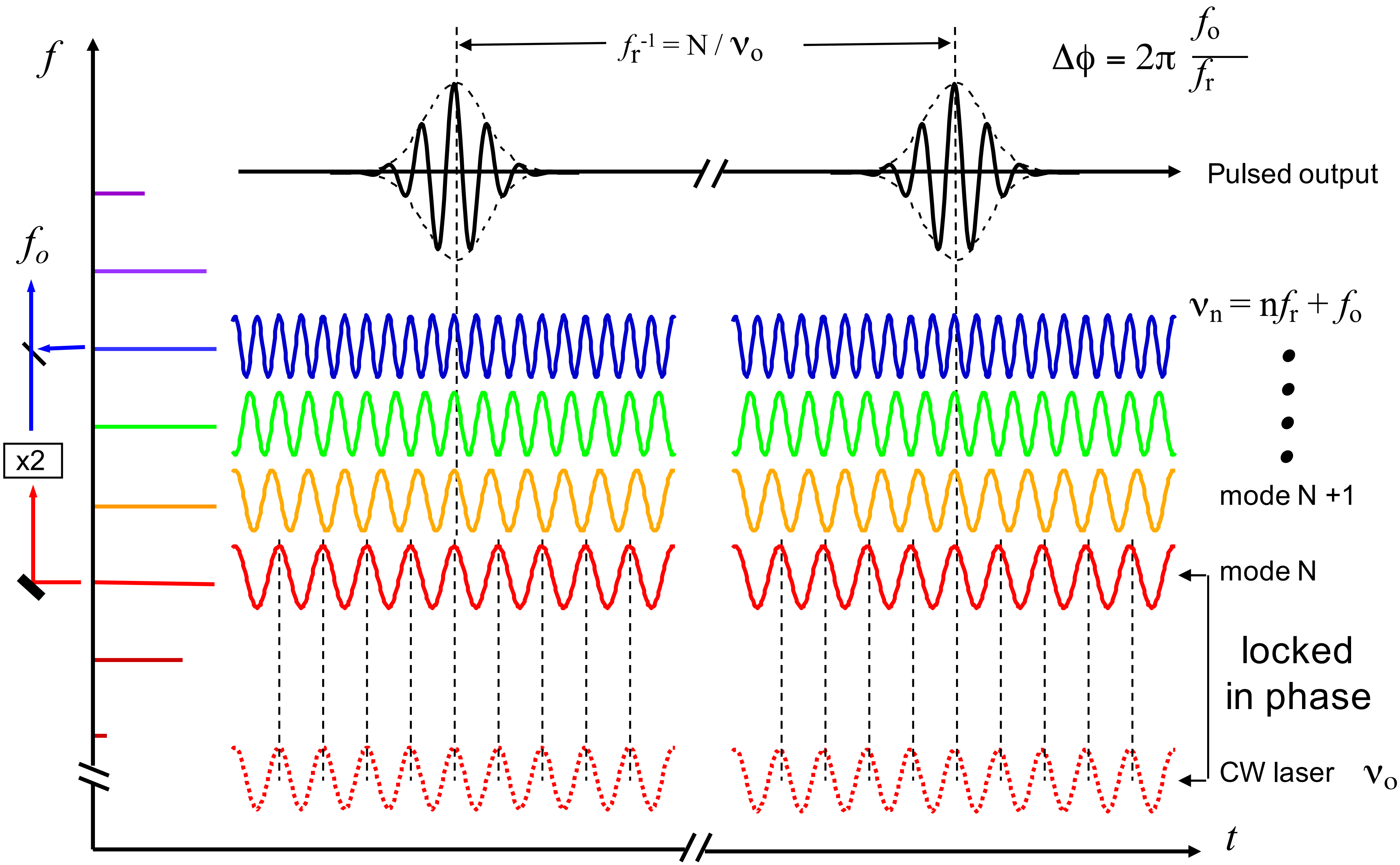
$$\nu_n = n f_r + f_o$$

- f_o measured by "self-referencing"

➢Need an octave-span spectrum

- f_r controlled with a microwave source or a CW laser

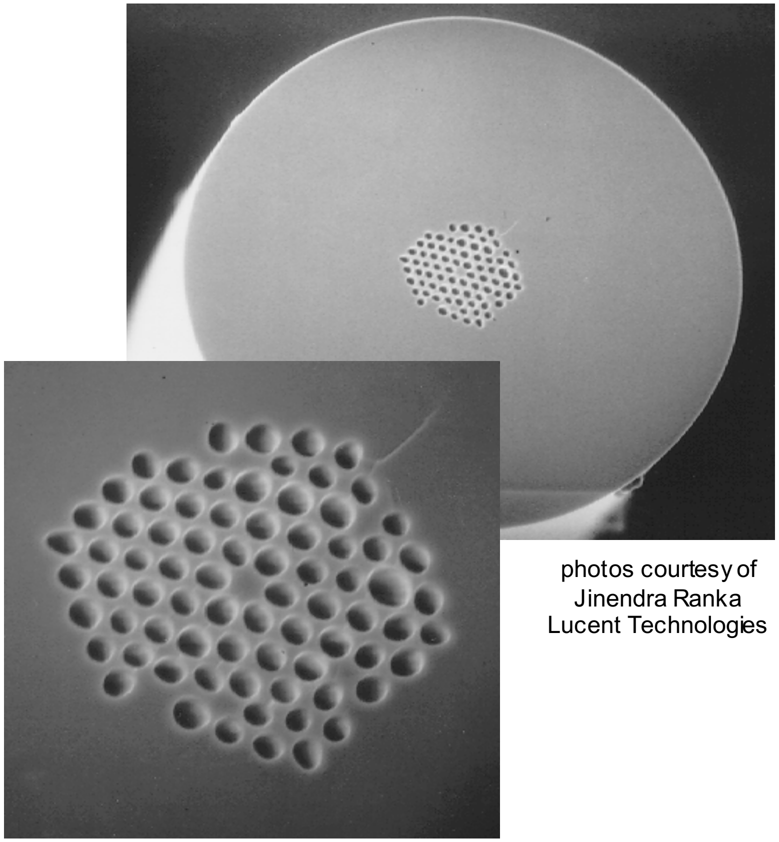
The laser comb and its control



Operation is fully reversible: Can lock at microwave and synthesize optical

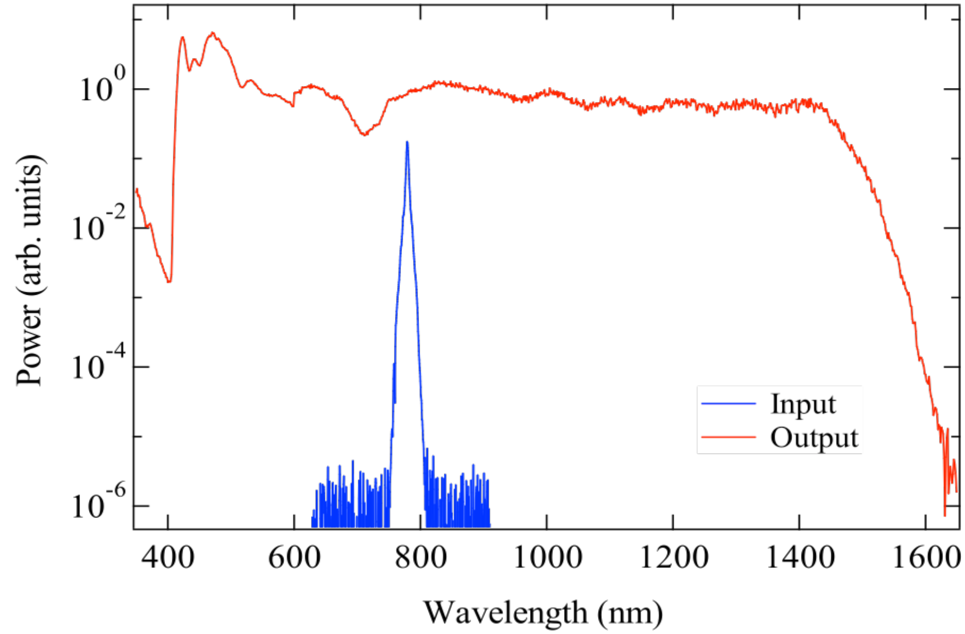
T. W. Hänsch and J. Hall, Nobel Lectures; D. J. Jones, et al., Science **288**, 635 (2000); S. Diddams, Th. Udem, et al., *Science* **293**, 825 (2001)

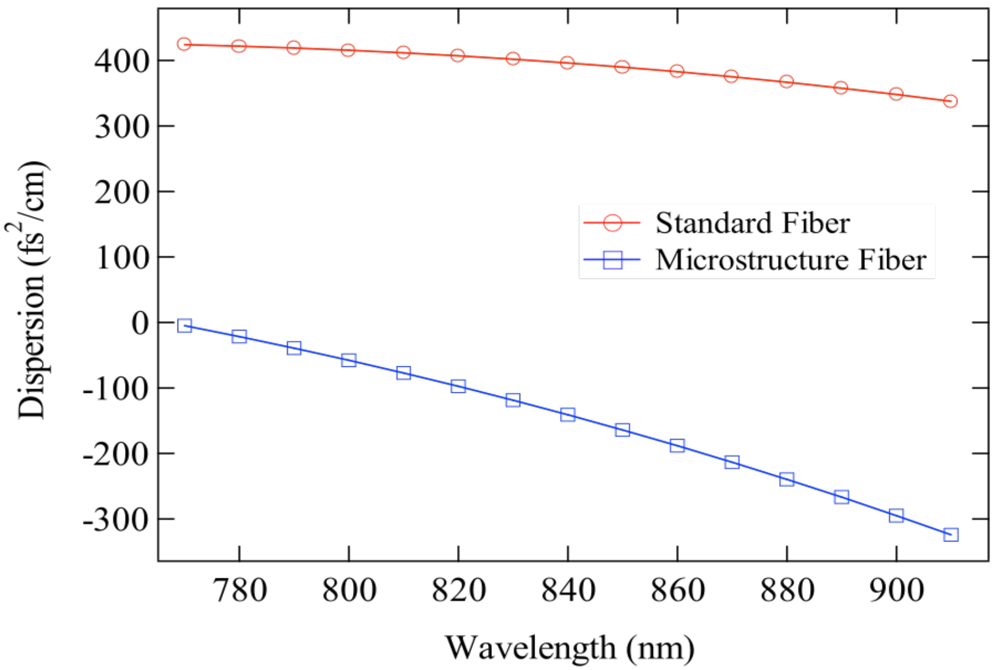
Microstructure optical fiber continuum generation



photos courtesy of
Jinendra Ranka
Lucent Technologies

CLEO Postdeadline (CPD8) Baltimore (1999).
J. Ranka, R. Windeler, A. Stentz, Opt. Lett. **25**, 25 (2000).



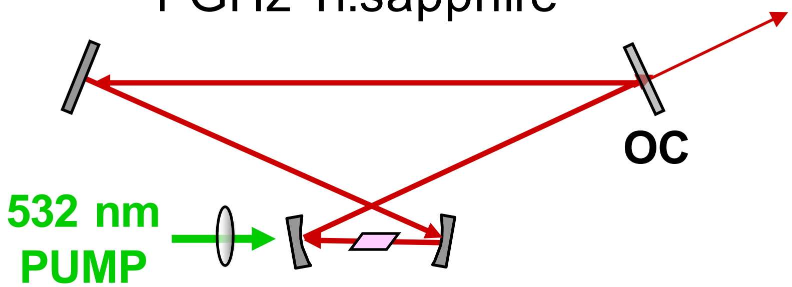


•Tight confinement of light leads to high nonlinearity and anomalous dispersion in the wavelength regime of femtosecond Ti:sapphire lasers

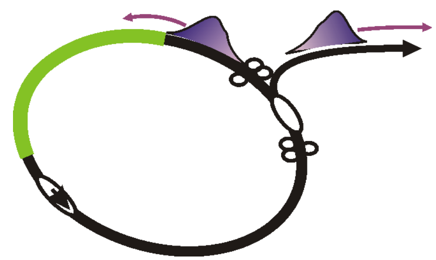
•Such fibers are available from commercial sources (ThorLabs, Crystal Fibre) and are developed in research labs (OFS, Univ. of Bath)

Octave-Span Supercontinuum

1 GHz Ti:sapphire

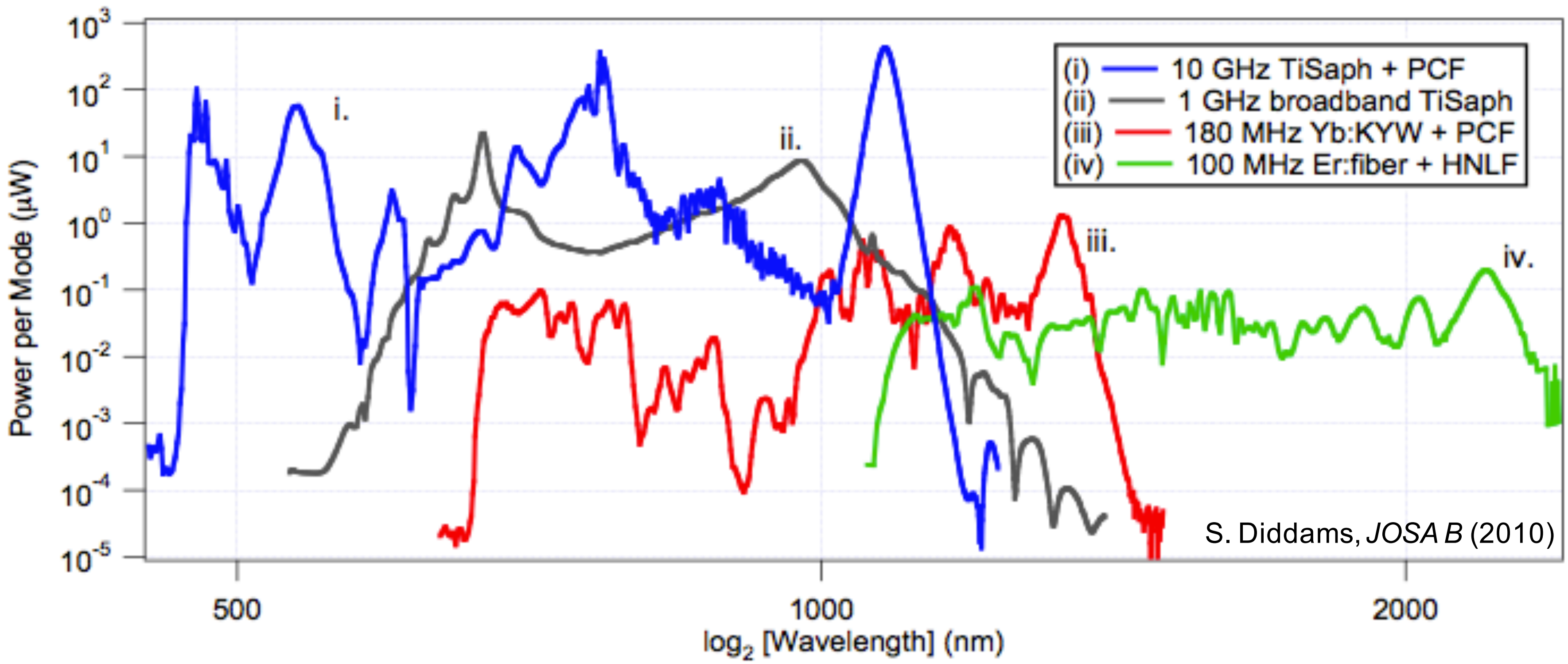


100 MHz Er:fiber



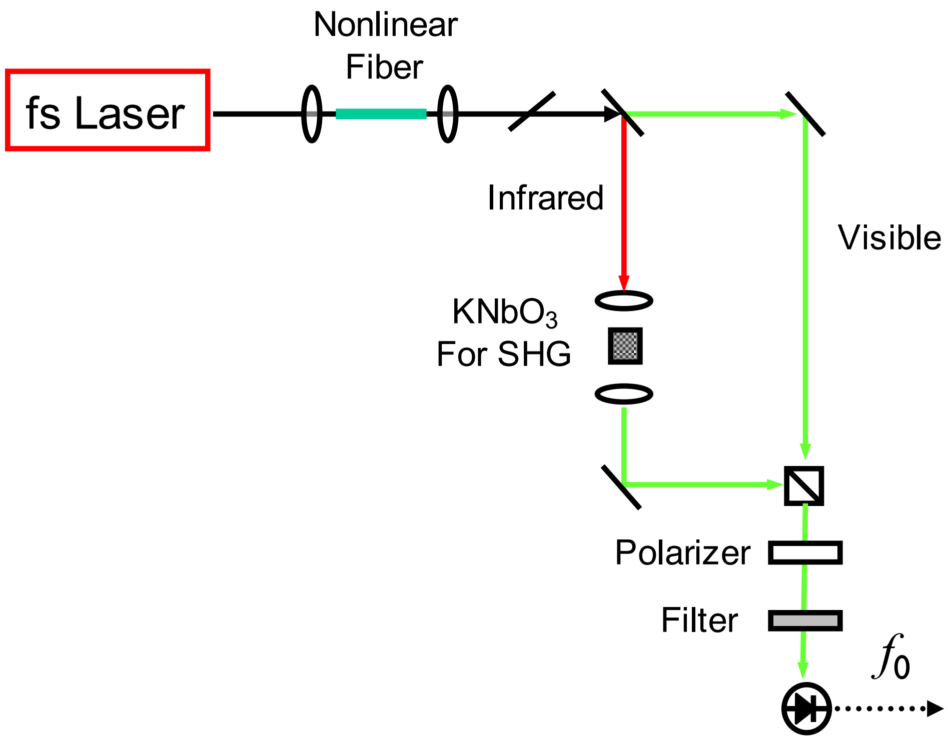
also….

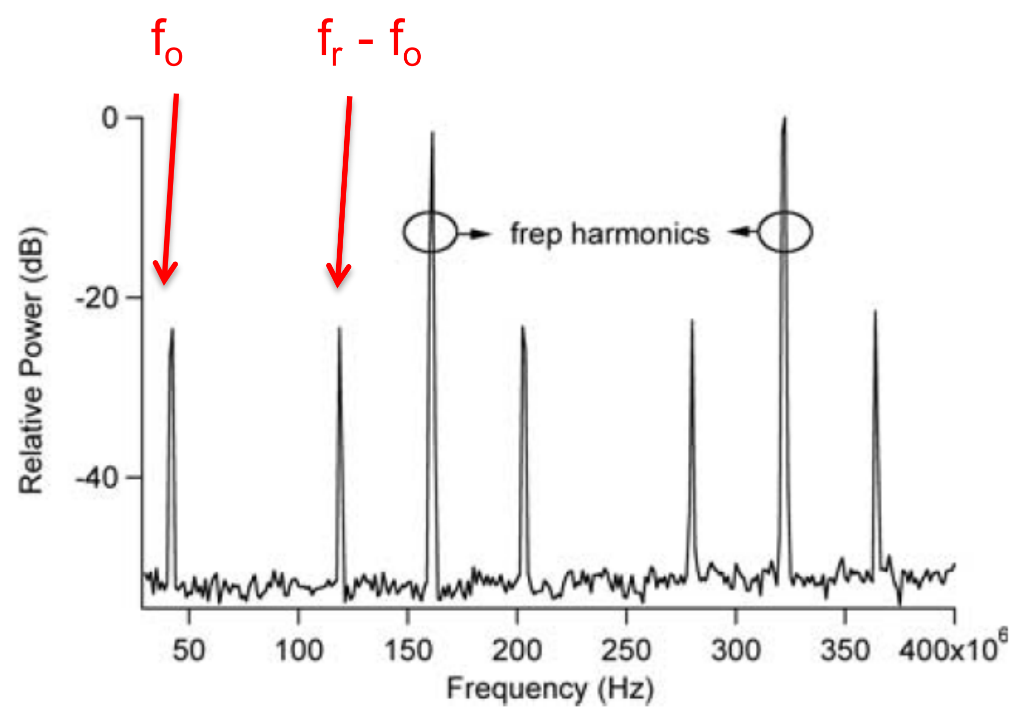
Yb:fiber
Yb:crystalline
Tm:fiber
…..



A. Bartels, H Kurz, *Opt. Lett.* **27**, 1839 (2002)
L. E. Nelson et al., *APB* **65**, (1997)

Nonlinear interferometer for measuring f_0





Other interferometer designs exist:

- inline with waveguide PPLN
- Michelson

First Self-Referenced Mode-locked Lasers

	Ti:Sapphire Jones 2000, Apolonski 2000	**Cr:LiSAF** Holzwarth 2001	**Er:fiber** Washburn 2004	**Cr:forster-ite** Kim 2005, 2006	**Yb:fiber** Hartl 2007	**Yb:KYW** Meyer 2008	**Er:Yb Glass** Stumpf 2009	**Tm:fiber** Phillips 2011
center λ	800 nm	894 nm	1560 nm	1275 nm	1040 nm	1030 nm	1560 nm	1950 nm
pulse length	~10-50 fs	~50 fs	80-200 fs	30 fs	70-100fs	290 fs	170 fs	70 fs
Pump source	532 nm, doubled Nd:YVO	650 nm diode	980 or 1480 nm diode	1075 nm fiber laser	976 nm diode	980 nm diode	976 nm diode	793 nm diode
Repetit-ion rate	0.1 - 10 GHz	93 MHz	50-300 MHz	420 MHz	0.1-1 GHz	180 MHz	75 MHz	72 MHz
E-to-O Efficiency	~0.1%	1-2%	~1%	~0.5%	1-2%	~2-3%	~2-3%	??

NIST

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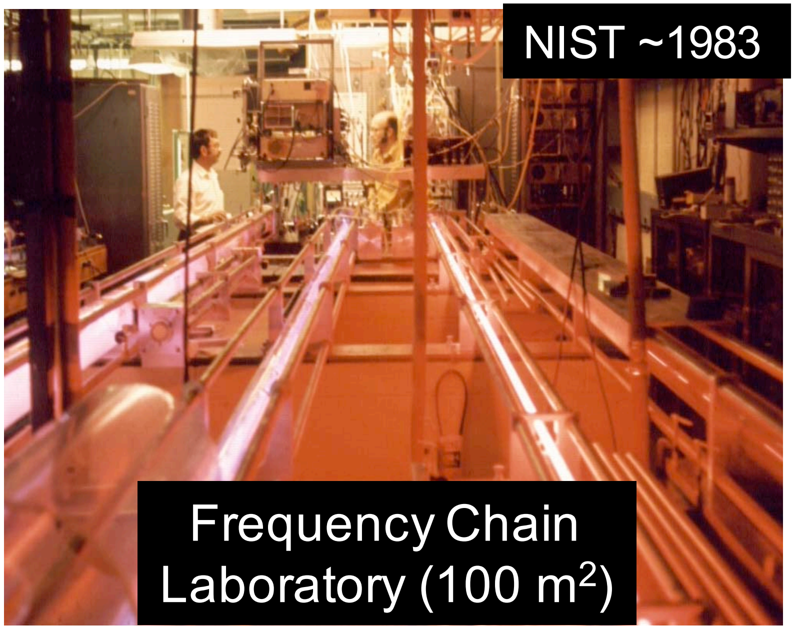
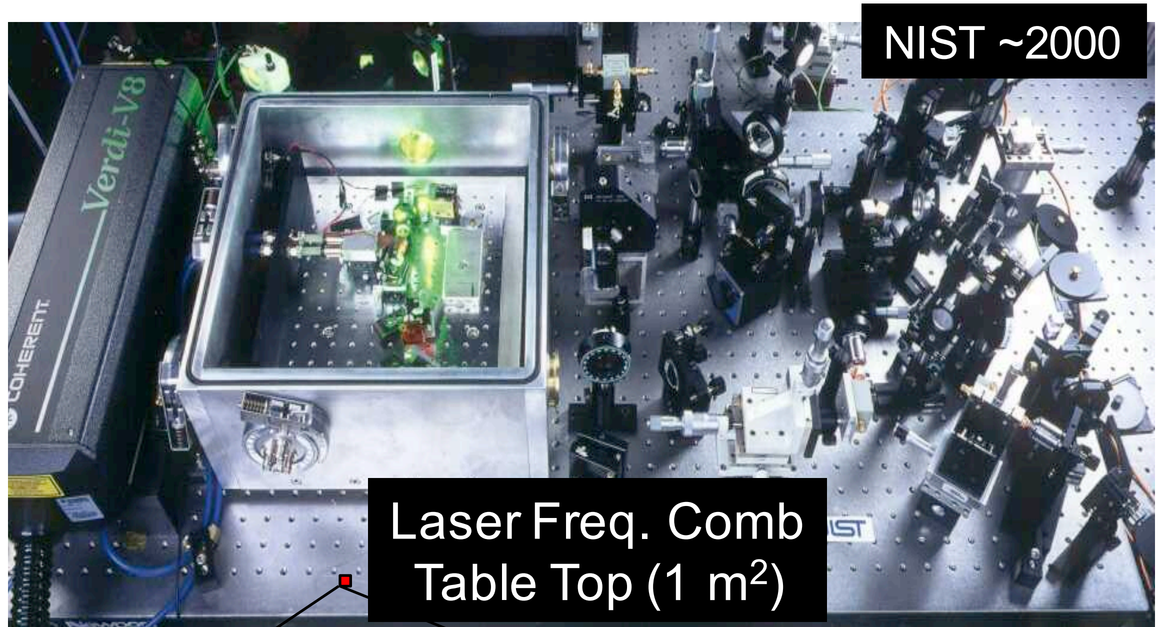
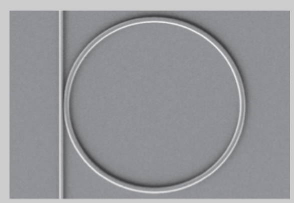
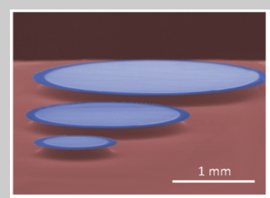
Moving from Lab Scale to Chip Scale





~10^4 size reduction





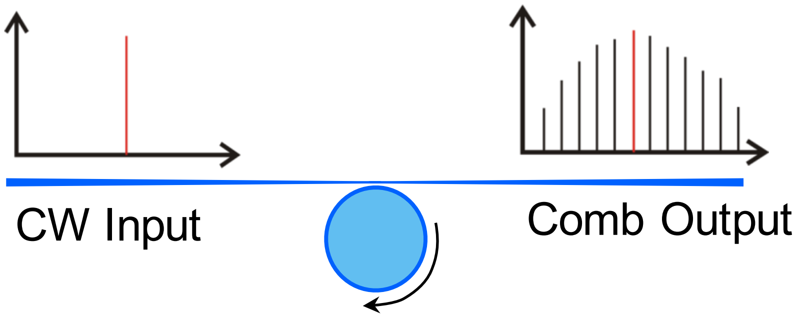
~1 cm^2

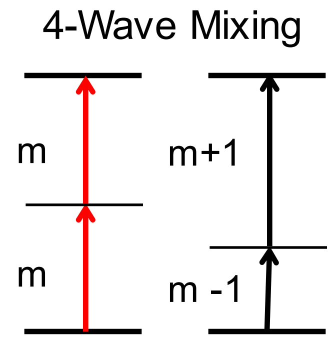
Future: Photonic Integrated Circuits

<u>Potential Impact:</u>

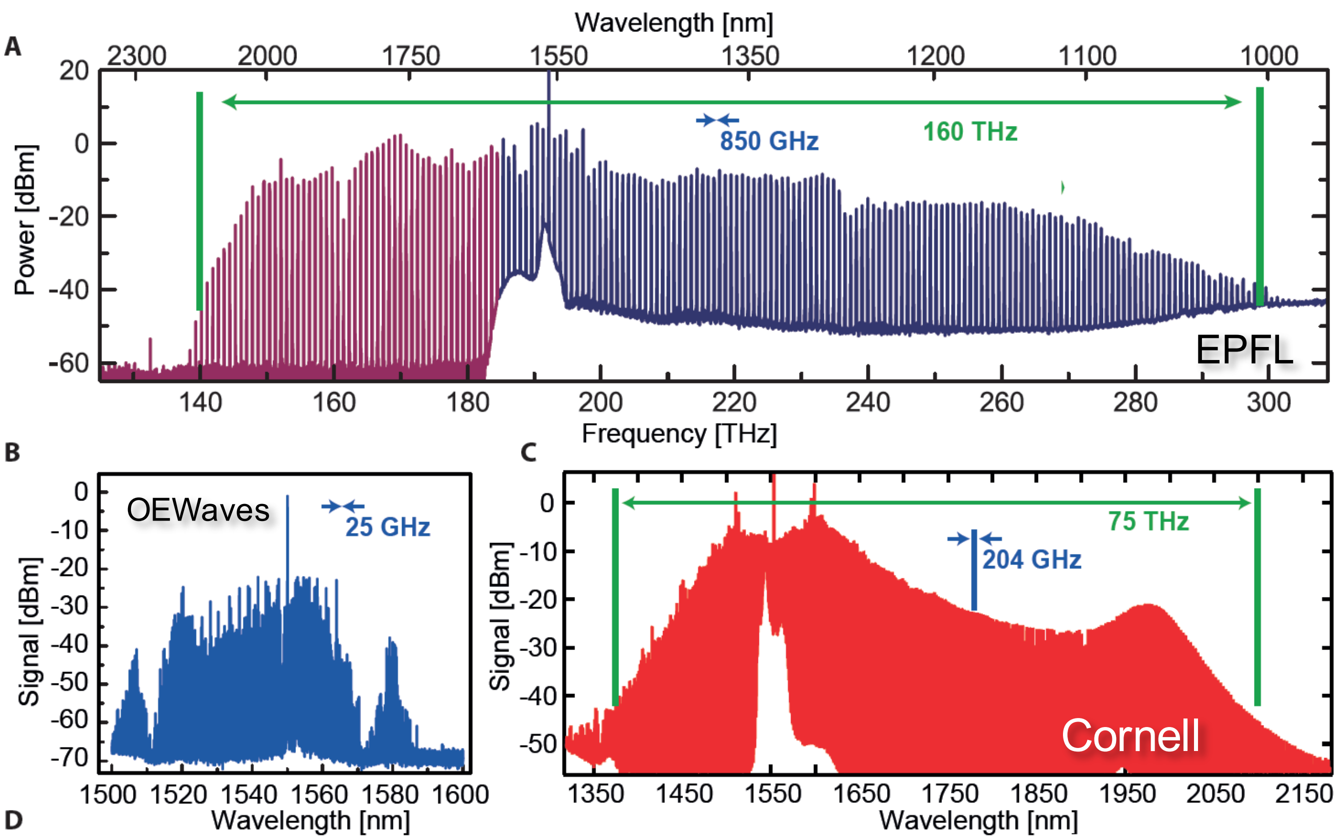
- Operation in any environment
- Chip scale clocks
- Inexpensive and mass produced
- Communication and navigation
- Sensing (environment, medical, manufacturing...)

A Tiny Revolution in Frequency Combs





1. Energy conservation:
   $2\omega_P = \omega_S + \omega_I$
2. Momentum conservation: linear + nonlinear
3. Line spacing given by resonator size

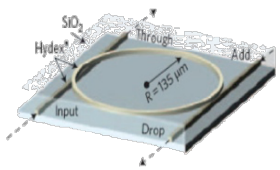


- Combs that appear regularly-spaced are possible, but not all are useful for metrology
- Understanding (controlling?) noise processes is critical
- What is happening in the time domain?

Del'Haye, et al., Nature **450**, 1214 (2007)
Kippenberg, Holzwarth, Diddams Science **332** , 555 (2011).

Microresonator Gallery

Hydex

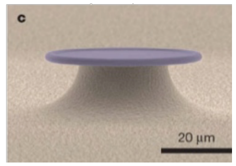


RMIT

Si:Nitride

Cornell,
Purdue, NIST
G-burg,
EPFL,
UCLA

Silica toroid

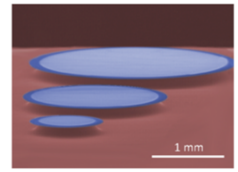


MPQ,
EPFL,
Caltech

Crystals

OEWaves
JPL
EPFL

Silica wedge

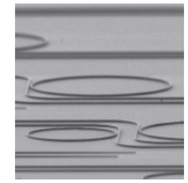


Caltech

Quartz

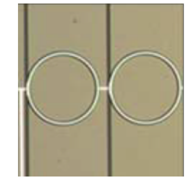
NIST

Diamond



Harvard

Al:Nitride



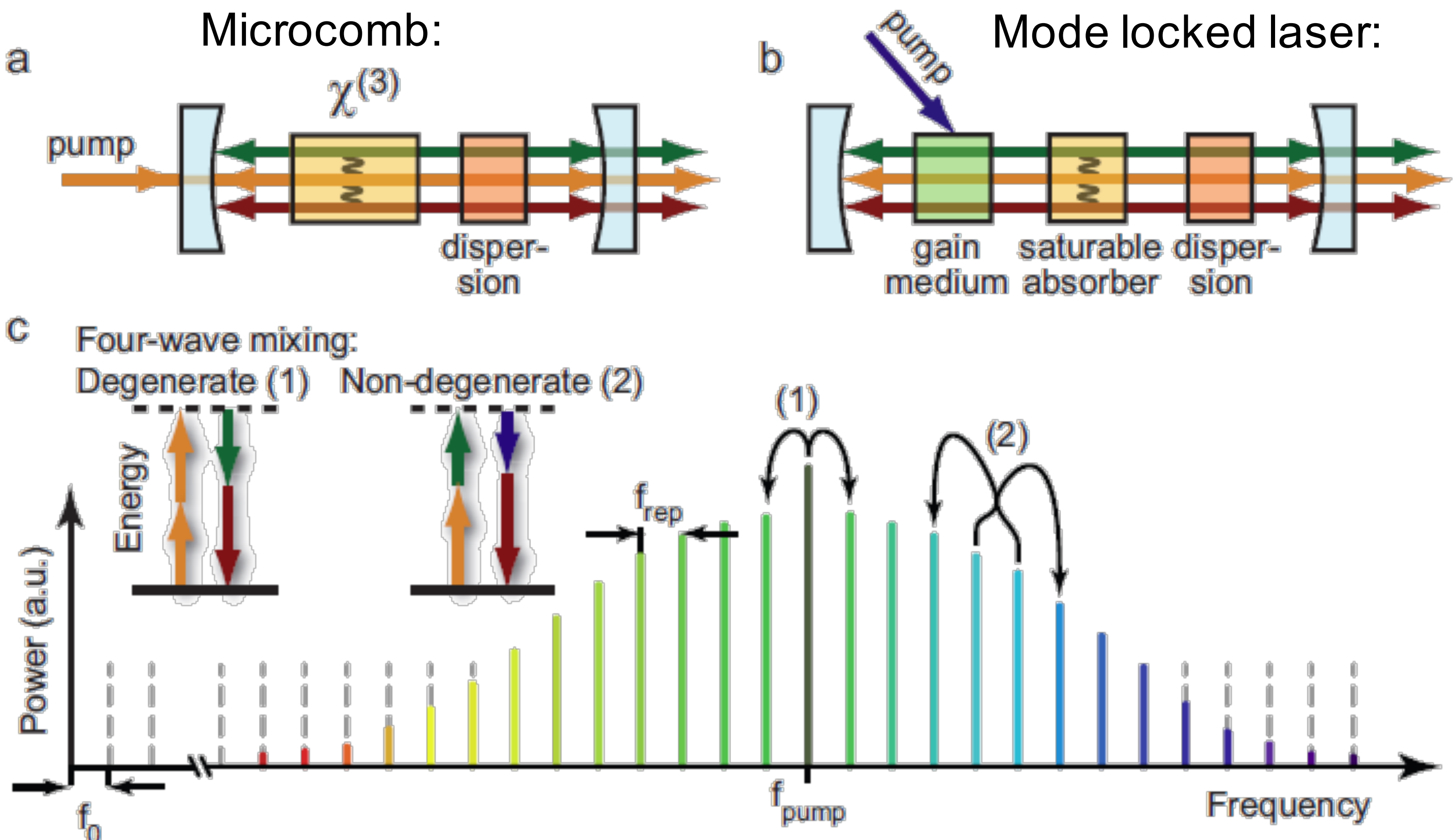
Yale

Key Properties

- High-Q cavity (>10^9)
- Small mode volume
- Mode-spacing given by perimeter
- Low & controllable dispersion
- Integrated chip-scale package

[1] L. Razzari, D. Duchesne, M. Ferrera, R. Morandotti, S. Chu, B. E. Little & D. J. Moss (Nature Photonics **4**, 41 – 45, 2010)
[2] J.S. Levy, A. Gondarenko, M.A. Foster, A.C. Turner-Foster, A.L. Gaeta & M. Lipson (Nature Photonics **4**, 37 – 40, 2010)
[3] P. Del'Haye, A. Schliesser, O. Arcizet, T. Wilken, R. Holzwarth, T. J. Kippenberg (Nature **450**, 1214-1217, 2007)
[4] A.A. Savchenkov, A.B. Matsko, V.S. Ilchenko, I.Solomatine, D. Seidel, and L. Maleki (Phys Rev Let. **101**, 093902, 2008)
[5] S.B. Papp and S.A. Diddams (PRA **84**, 053833, 2011)
[5] F. Ferdous, H. Miao, D. E. Leaird, K. Srinivasan, J. Wang, L. Chen, L. T. Varghese & A. M. Weiner (Nature Photonics **5**, 770, 2011)

Comb Generation Principle

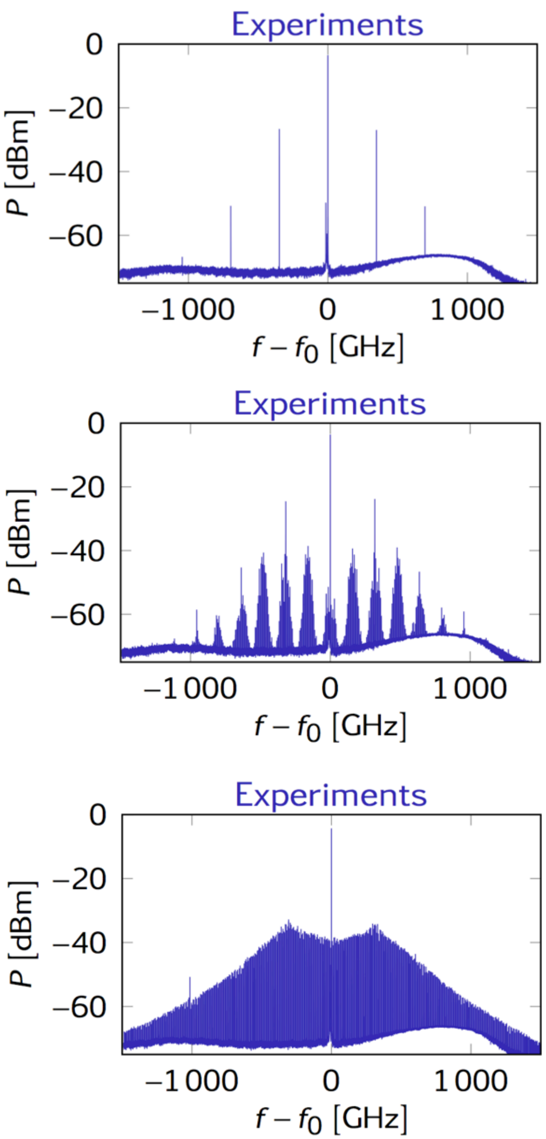


Microcomb:

- Parametric gain vs. stimulated emission
- Pump laser part of comb (offset tuning)
- No saturable absorber

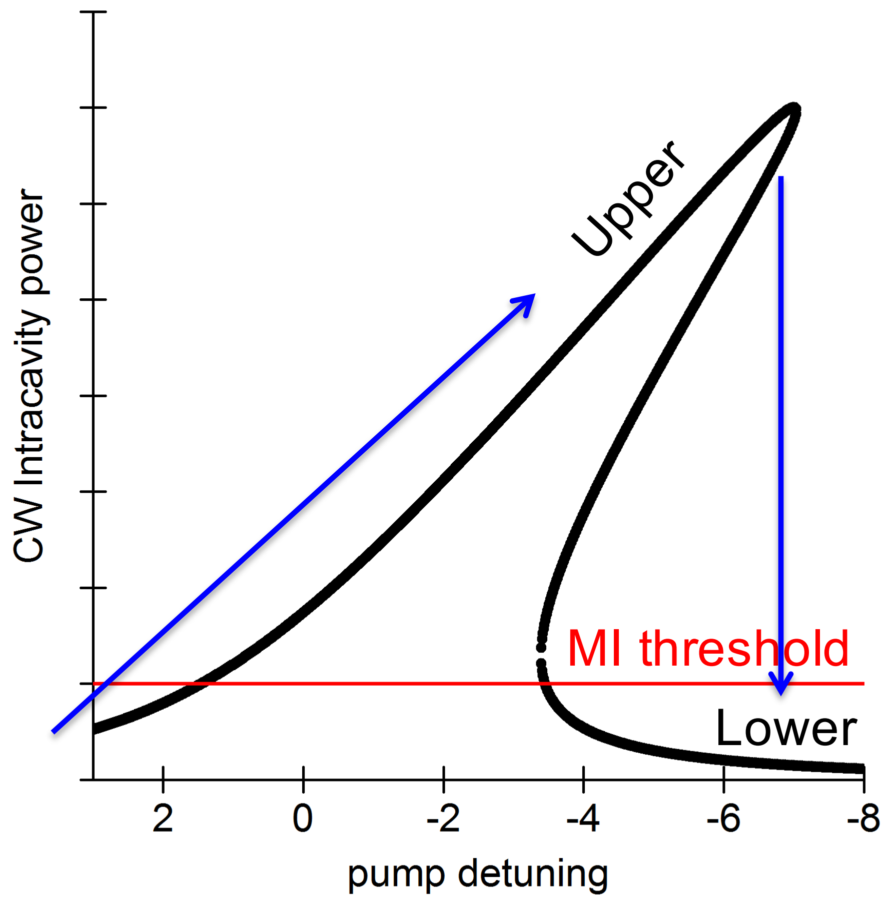
Kerr Microcomb Formation

Upper branch:
Modulation instability

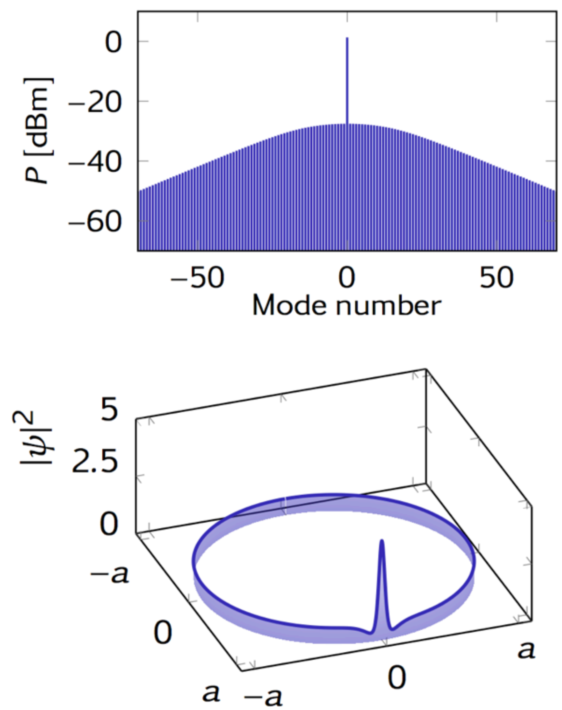


Kerr-nonlinear microcavity

$$\frac{\partial E}{\partial t} = -(1+i\Delta)E + i\left|E\right|^2 E - i\frac{\beta}{2}\frac{\partial^2 E}{\partial \theta^2} + F$$



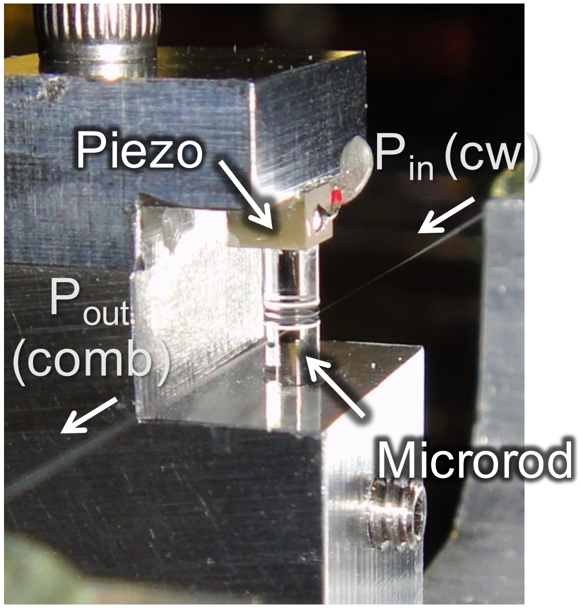
Lower branch:
Cavity soliton



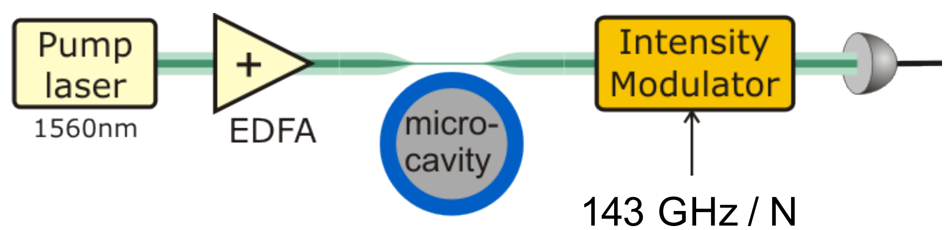
Frequency control of microcombs

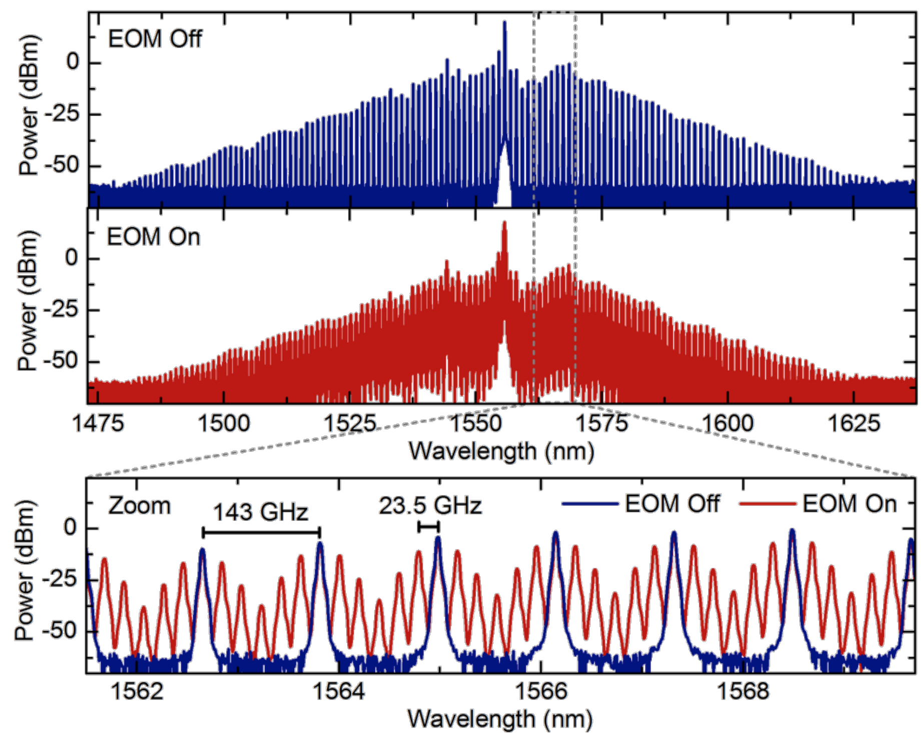
Demonstrated Frequency Control: <10^{-15} at 1s

Mechanical control (wide BW)

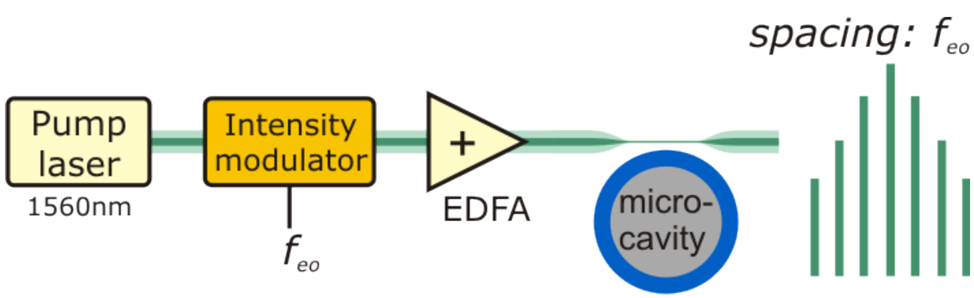


Hybrid EOM + microcomb (high rep. rate)



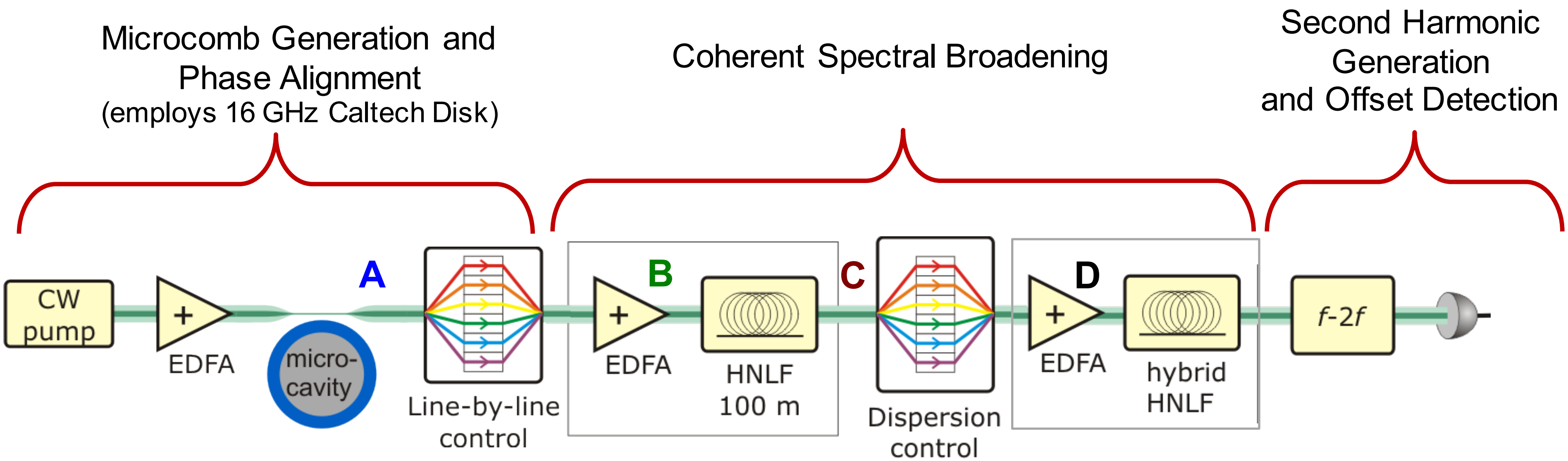


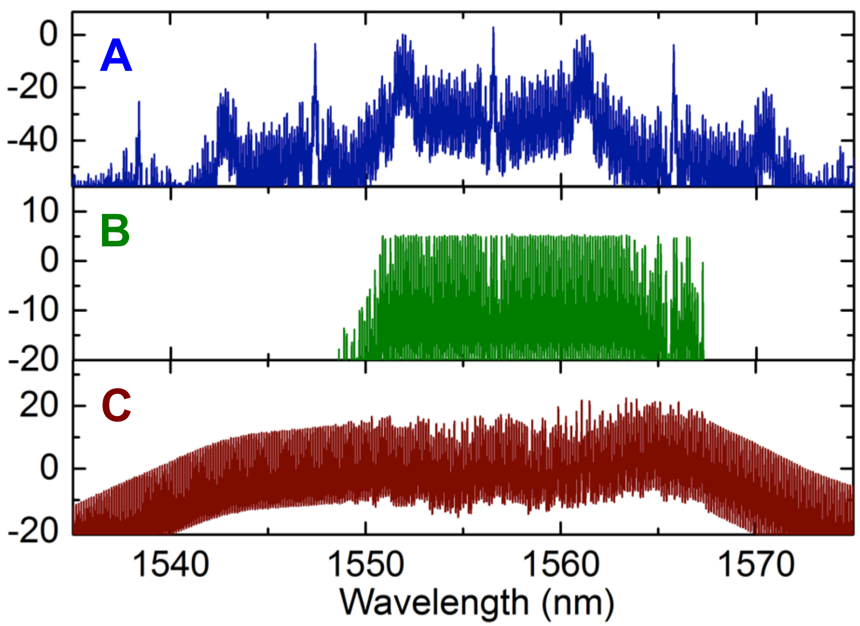
Parametric seeding (deterministic control)

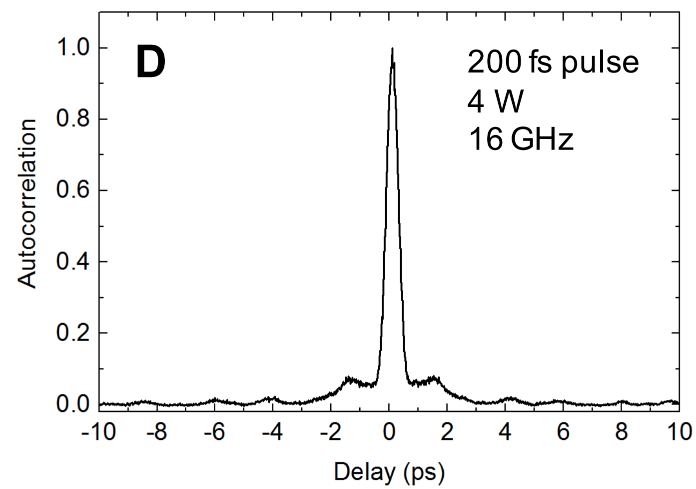


NIST

Self-Referencing a Microcomb



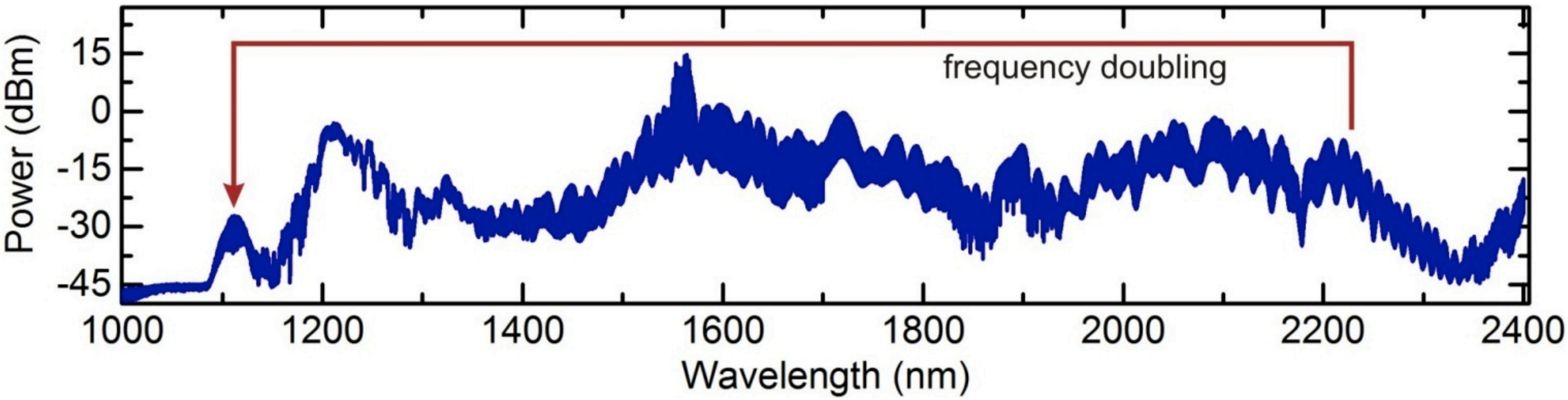




Pascal Del'Haye, Aurélien Coillet
also: Kippenberg group

NIST

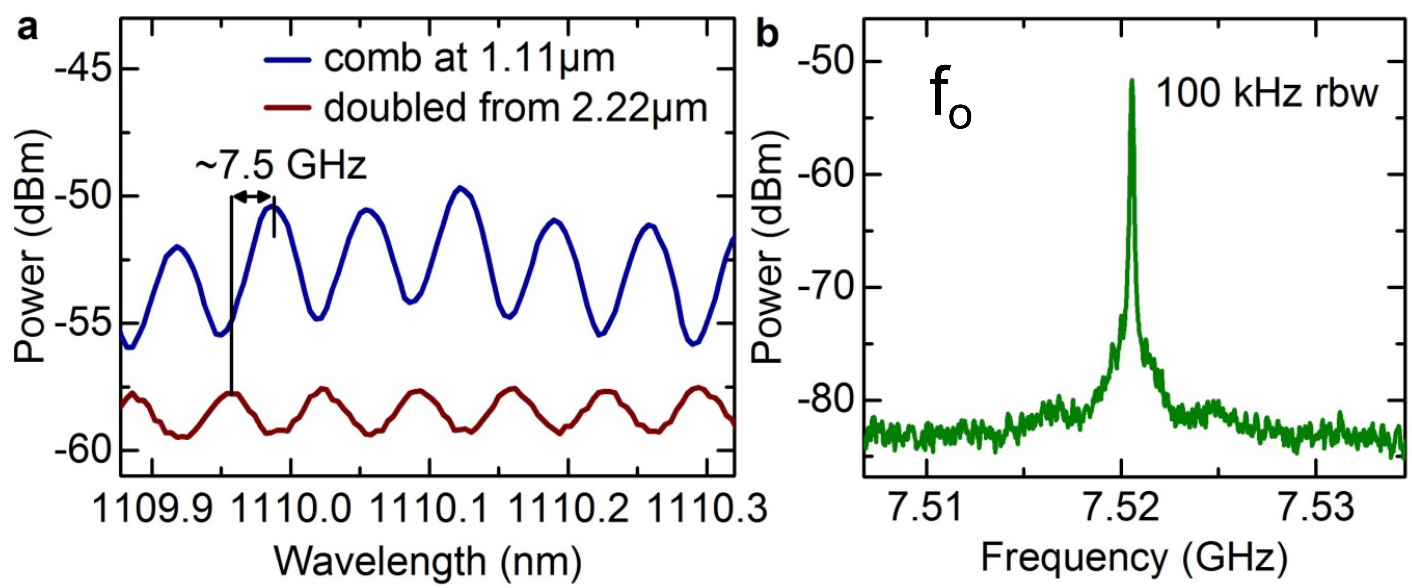
Self-Referencing a Microcomb



f-2f self-referencing

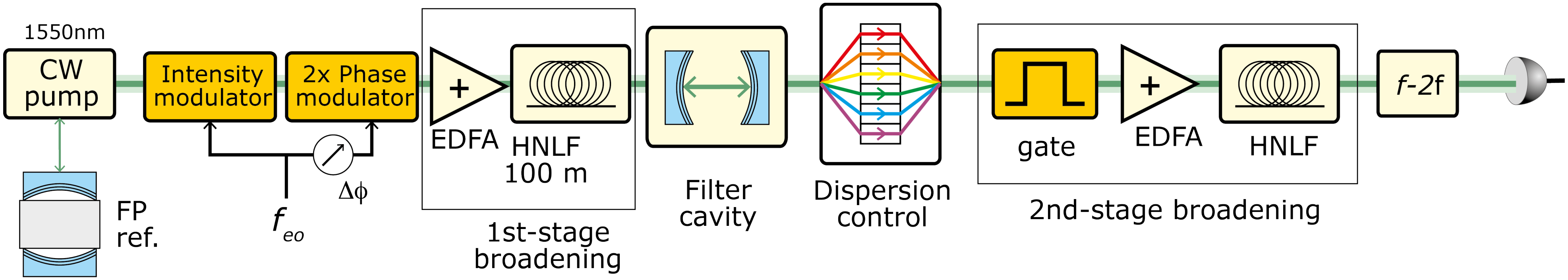
Highest reprate for self-referencing (16.4 GHz)

Highest measured f_o (7.5 GHz)

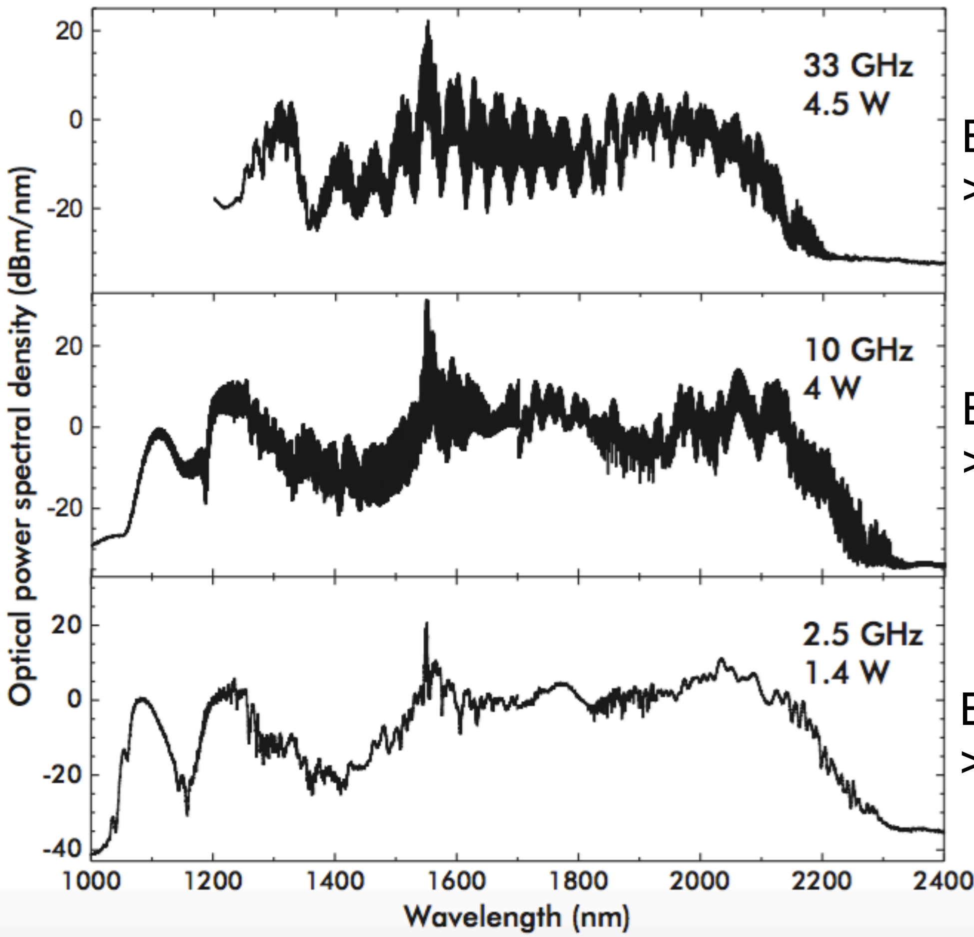


NIST

EOM Comb: Self-referencing a CW laser



see Scott Papp's talk



E_{pulse}= 120 pJ
> 2/3 octave

E_{pulse}= 450 pJ
> octave

E_{pulse}= 560 pJ
> octave

External broadening

Dual-stage pulse compression, amplification, and nonlinear broadening

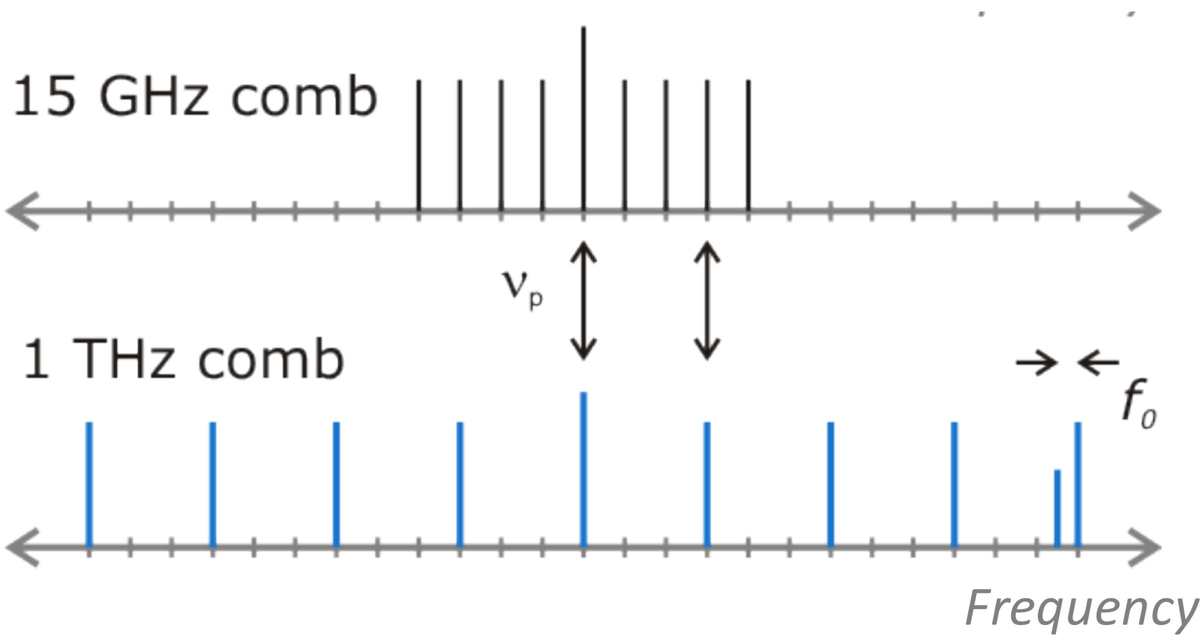
+

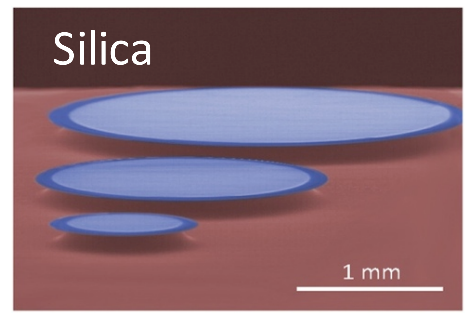
Frequency noise control

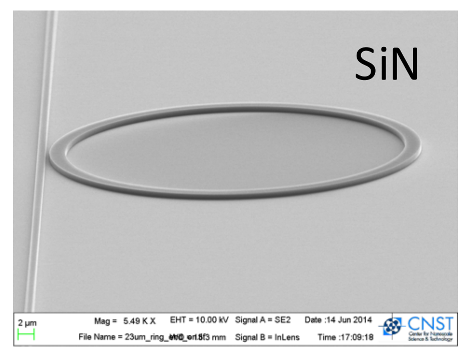
Myslivets et al., Opt. Exp., **20**, 3331 (2012)
Ishizawa et al., Opt. Exp.,**19**, 22402 (2011)
Cole et al., arXiv:1310.4134 (2013)
Beha et al., arXiv (2015)

Self-referencing on a chip?

Goal: An octave-span, self-referenced microcomb on a chip
Challenges: Power, frequency control & basic nonlinear optics
Approach: Dual reduction gear 200 THz → 1 THz → 15 GHz
Leverage: Photonic integration (pump laser, PPLN, photodiodes)

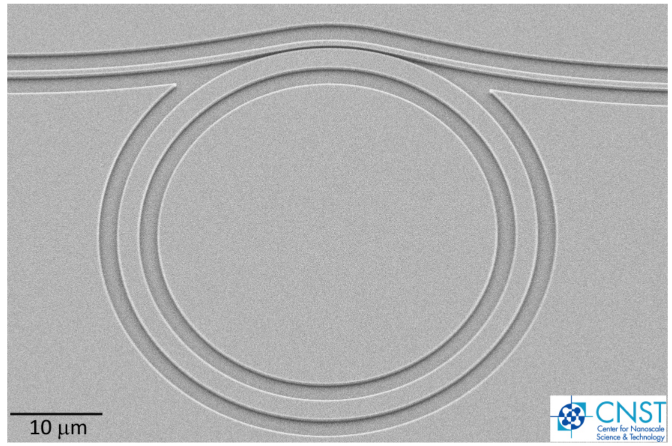






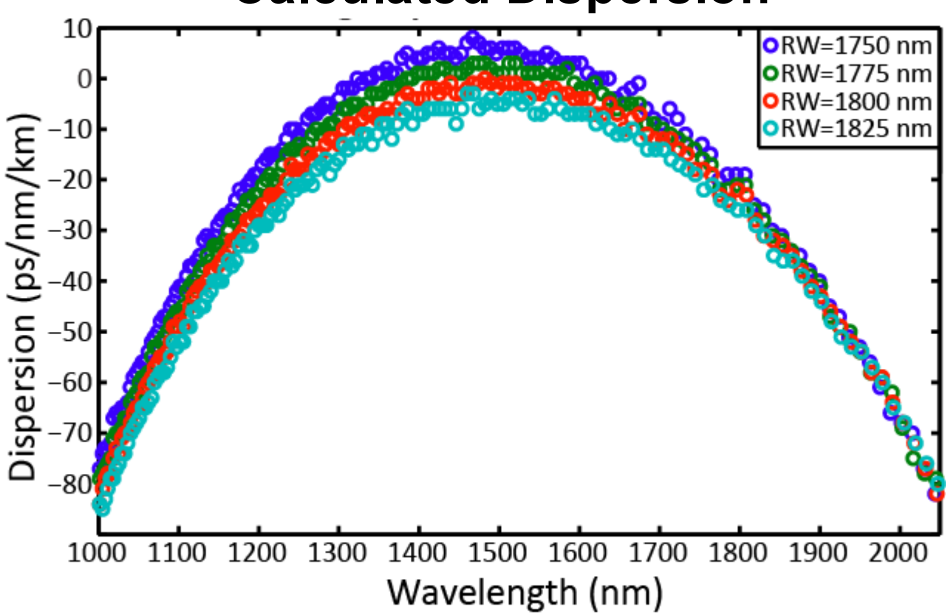
THz microcomb chip

1 THz SiN resonator

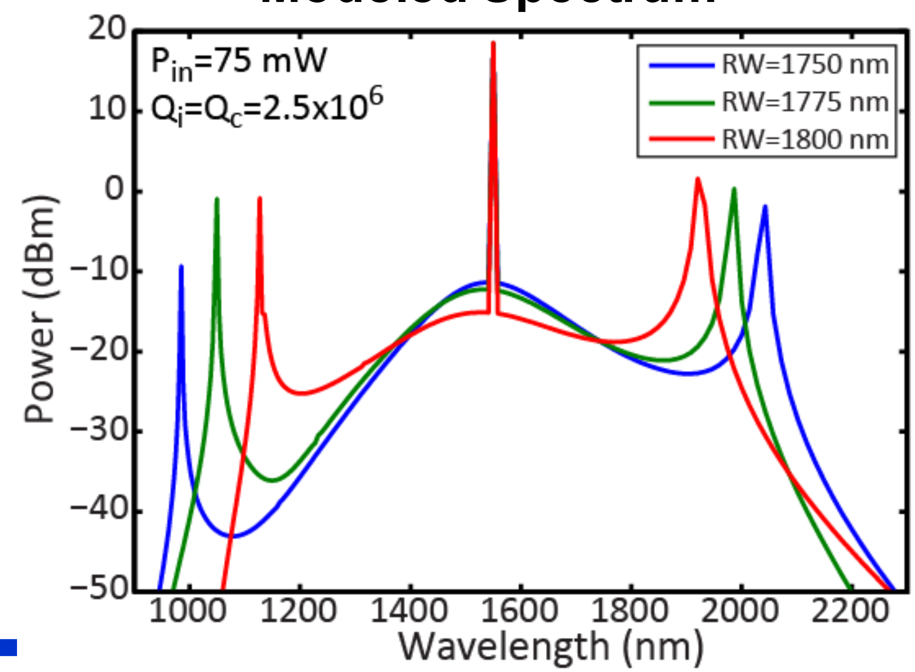


Kartik Srinivasan
Qing Li
Daron Westly

Calculated Dispersion

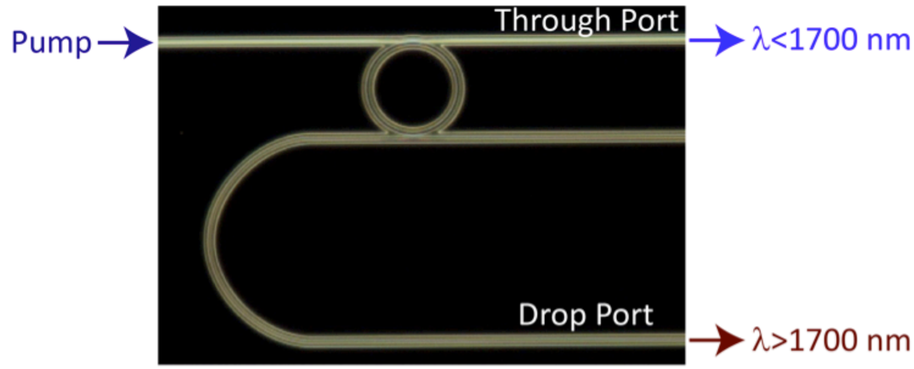


Modeled Spectrum

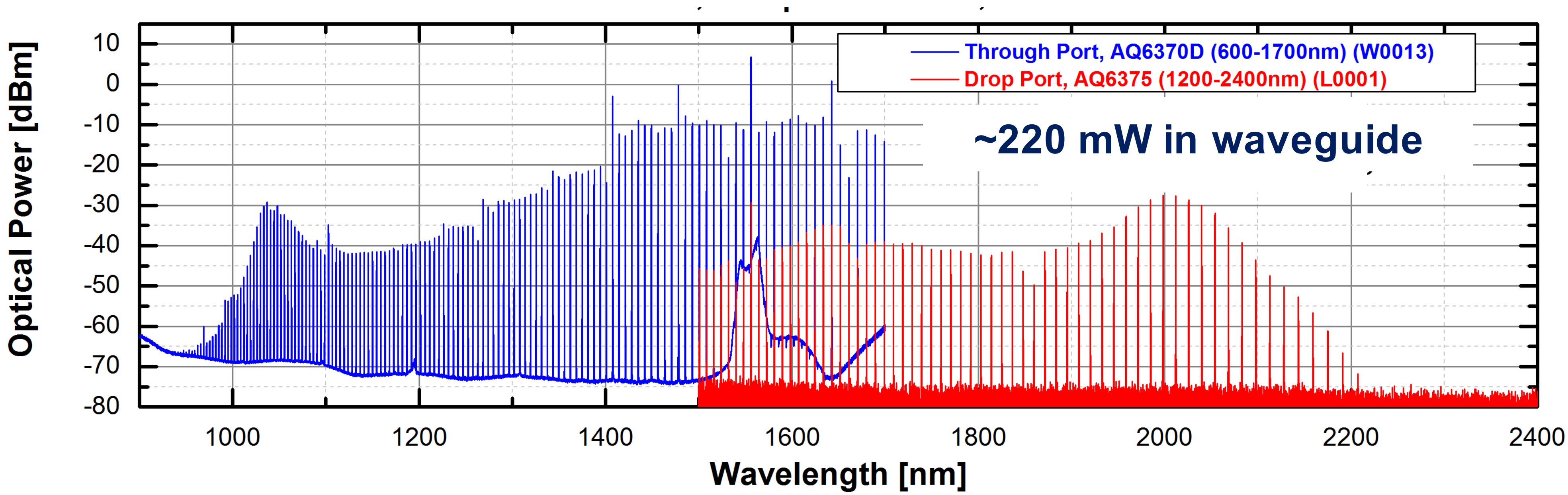


Octave Span & Dual Dispersive Waves

- dual dispersive waves via dispersion engineering
- "through" and "drop" ports provide optimal out-coupling of 1000 and 2000 nm



Travis Briles

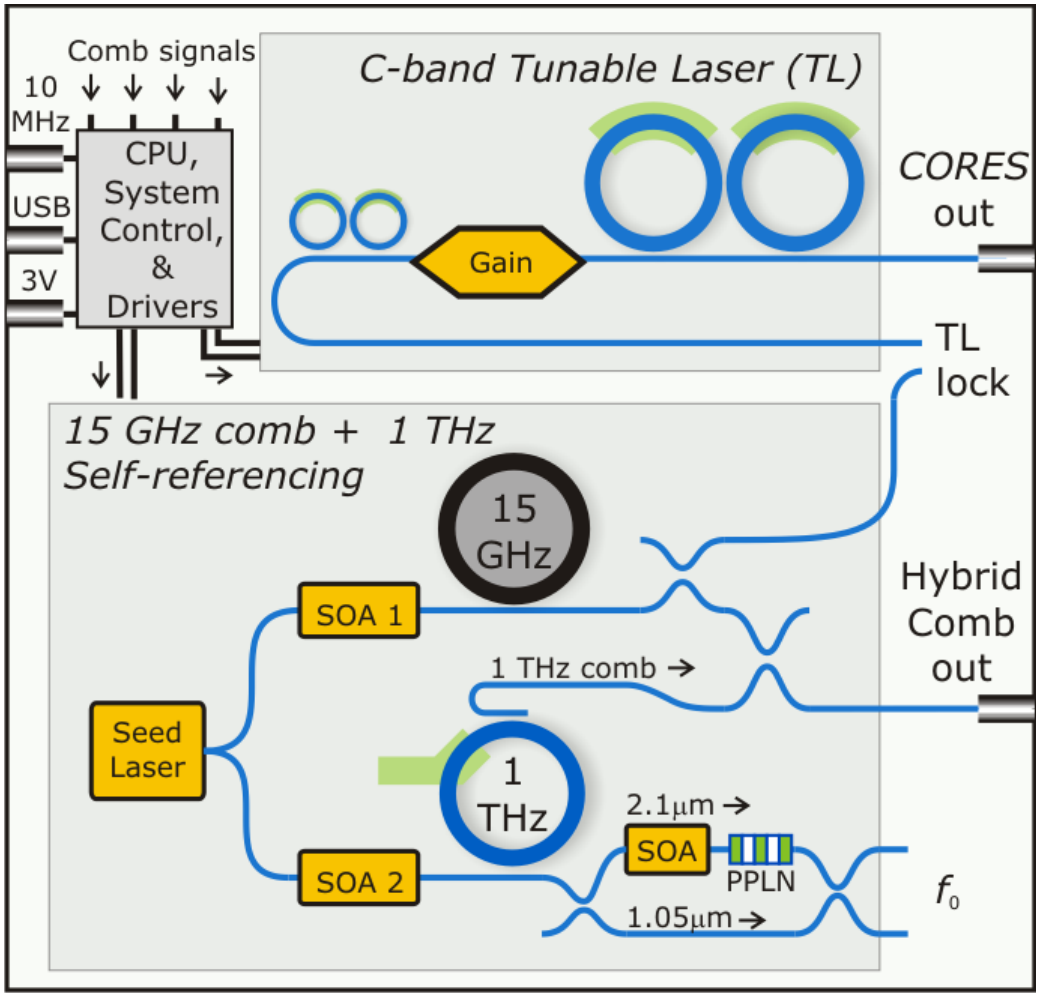


Next Steps:

- Low-noise solitons
- f-2f nonlinear interferometry (fine tune mode frequencies)

The future: Heterogeneous integration

- Self-referenced comb on a silicon chip
- Included pump and tunable laser output
- Could also include electronic control



Outline

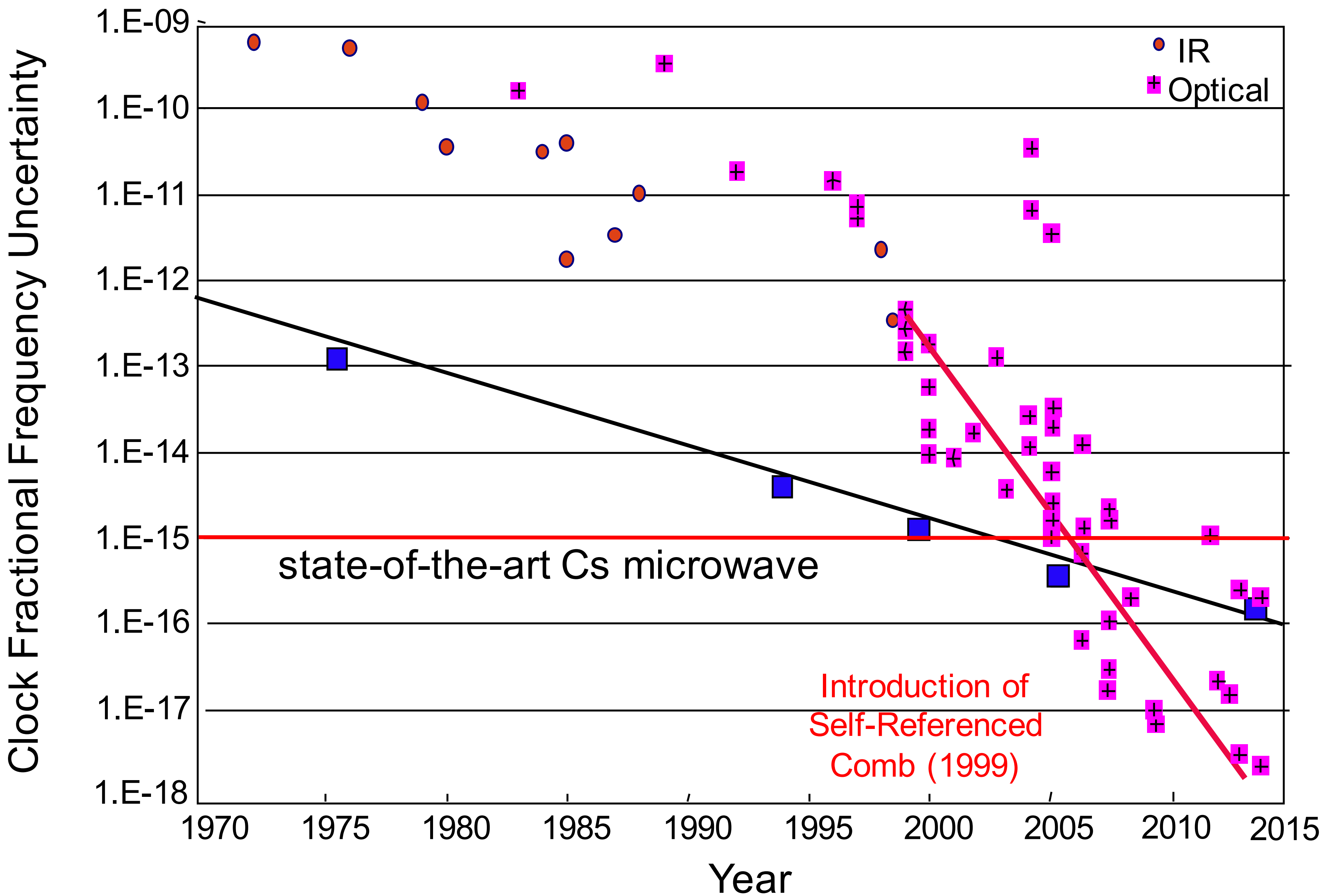
1. **Optical frequency combs in timekeeping**
   - How we got to where we are now….

2. **The multiple faces of an optical frequency comb**

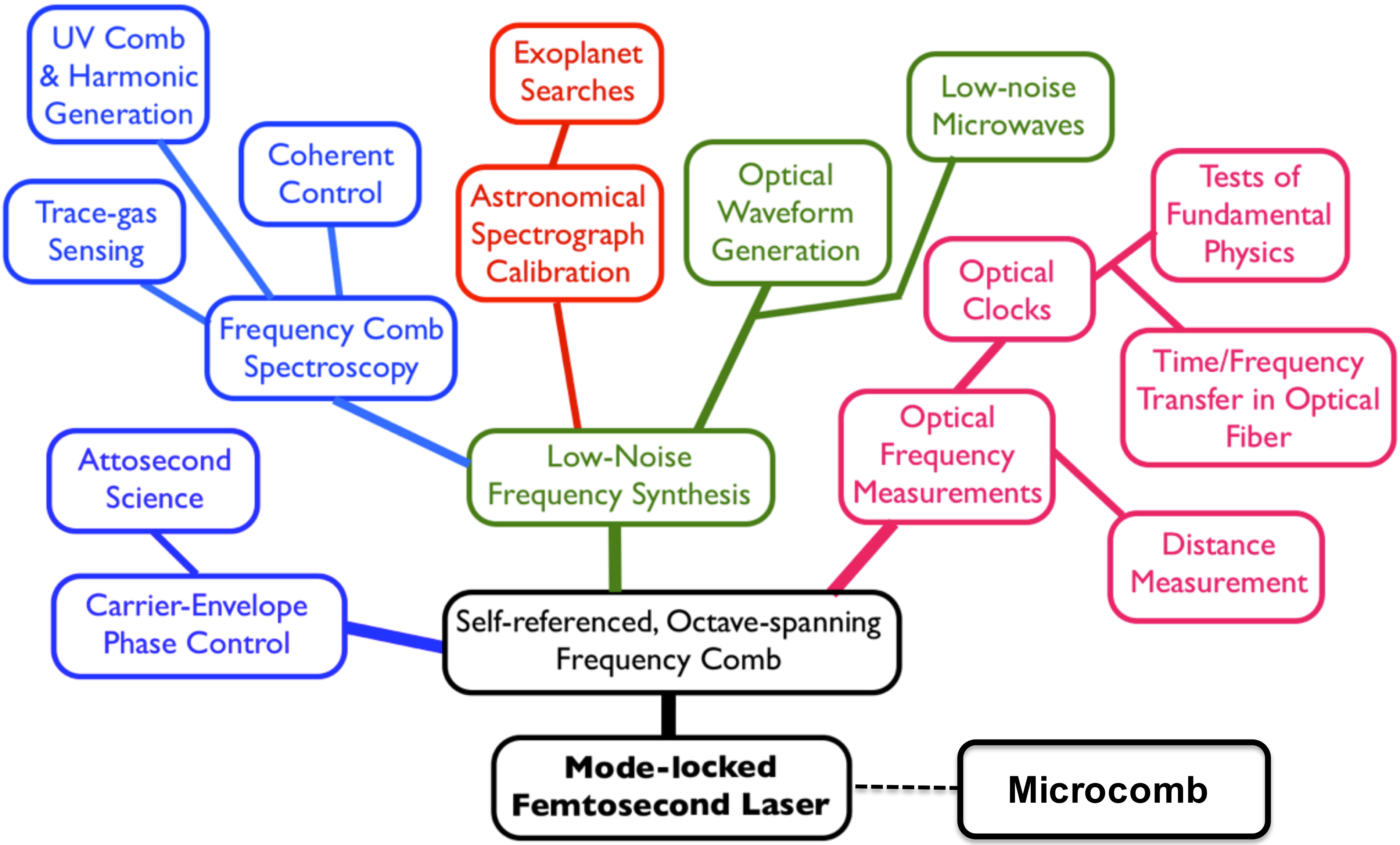
3. **Classes of frequency combs and their basic operation principles**
   - Mode-locked lasers
   - Microcombs
   - Electro-optic frequency combs

4. **Challenges and opportunities for frequency combs**

Frequency Combs and Clocks



Broad Range of Applications Beyond Clocks



Challenges/Opportunities

1. Gaps in our knowledge
    - Microcomb nonlinear optics and operation for full control and optimization of a low-noise, broad bandwidth spectrum
    - Fiber combs employ an “empirical recipe”
2. Technology is complex: Improved robustness, space worthiness....
3. Materials & systems
    - Improved nonlinear optics (integrated fiber and waveguide) more compatible with low power
    - New materials coming online (MIR, QCLs)
    - Best platform/material for different wavelength regions
4. Integration
5. Matching the technology to the application

Thank you!

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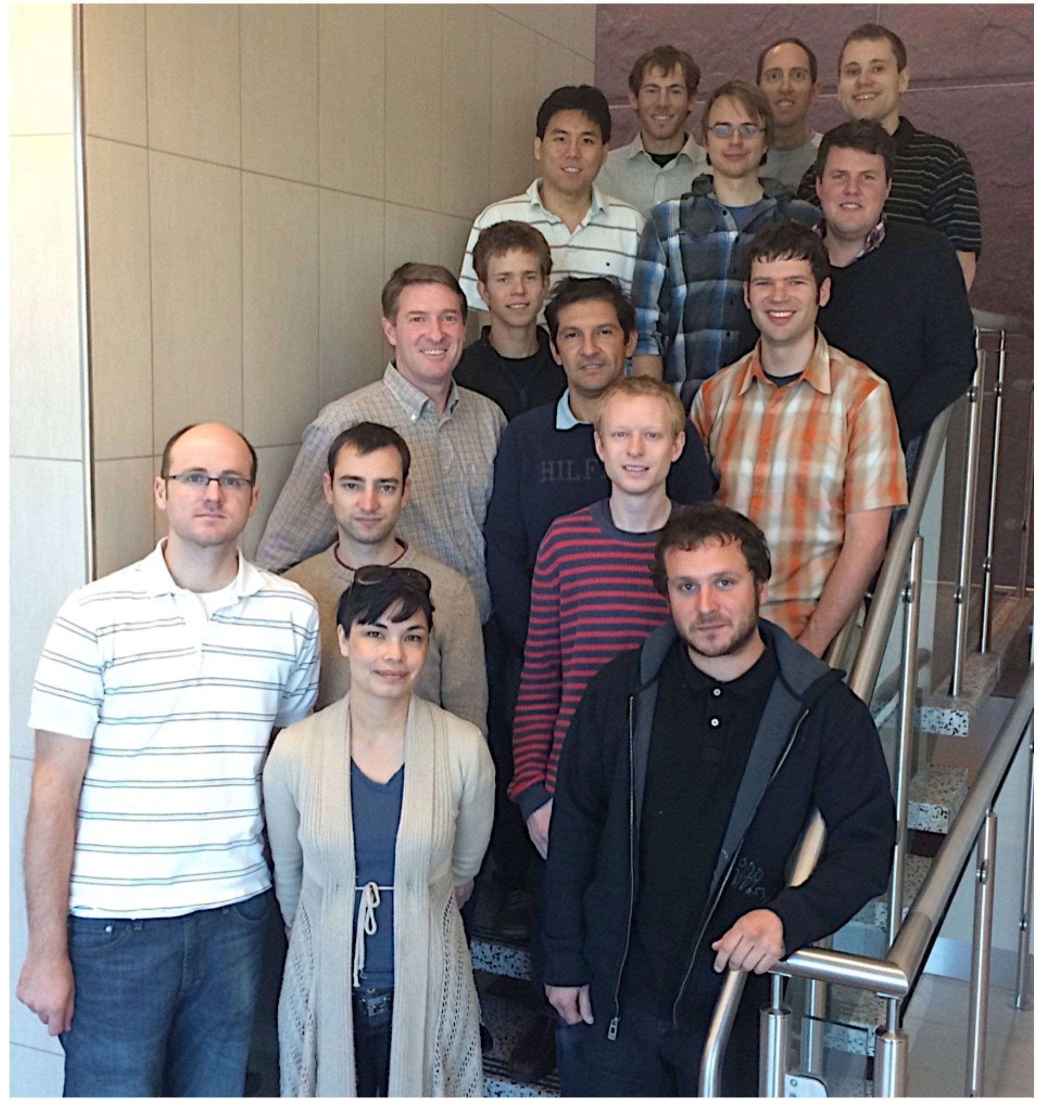
Visitors: Yi-Chen Chuang, Flavio Cruz, Francisco Senna

Collaborators: John Bowers (UCSB), Joe Campbell (Virginia), Kartik Srinivasan (NIST Gaithersburg), Kerry Vahala (Caltech)



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Funding: NIST, DARPA, AFOSR, NASA, NRC