Direct Frequency Comb Spectroscopy on Gas-filled Fiber References

Kristan L. Corwin

KANSAS STATE UNIVERSITY

Contributors

Grad Students:

Neda Dadashzadeh
Kushan Weerasinghe
Sajed Zavareh
Mary Harner, M.S.
Rajesh Kadel, Ph.D.
Turghun Maitinyazi, M.S.
Shun Wu, Ph. D.
Chenchen Wang, Ph.D.
Andrew Jones, Ph.D.
Kevin Knabe, Ph.D.
Jinkang Lim, Ph.D.
Rajesh Thapa, Ph.D.
May Ebbini, M.S.
Mohammed Faheem, M.S.

Post Docs:

Manasa Thirugnanasambandam
William Hageman
Karl Tillman
Ahmer Naweed

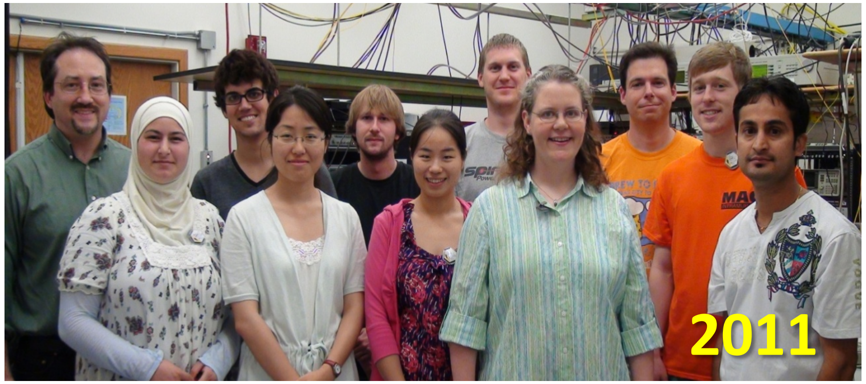
Visitors:

Yishan Wang
Hu

Faculty:

Brian Washburn

And many undergraduates, including:
Ryan Luder



Acknowledgements

- Collaborators:
  - Fetah Benabid's group at U. of Bath; XLIM, Limoges
  - Wolfgang Rudolph, Vasu Nampoothiri, and UNM group

- Thanks to:
  - Scott Diddams, Henry Kapteyn, Mike Kirshner, Nate Newbury, Jeff Nicholson, Sarah Gilbert, Bill Swann, Kurt Vogel
  - Larry Weaver, Brett DePaola, Mikes Wells and the JRM staff

- Current Funding:
  - AFOSR

- Past funding:
  - AFOSR & DEPSCoR, NSF CAREER, ARO STTR (Precision Photonics) , Kansas NSF EPSCoR program, Kansas Technology Enterprise Corporation

- Thanks ICTP!

Outline

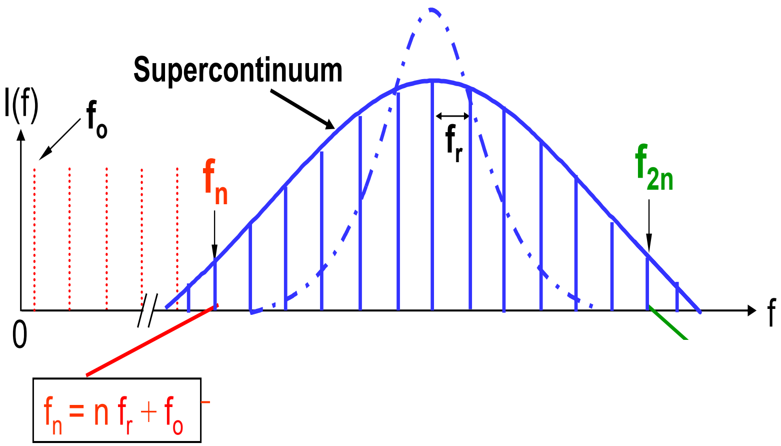
I. Gas-filled hollow fiber frequency references
- Near-IR Portable frequency references in 2001
  - Acetylene gas
- Goal: Sub-Doppler and portable frequency reference

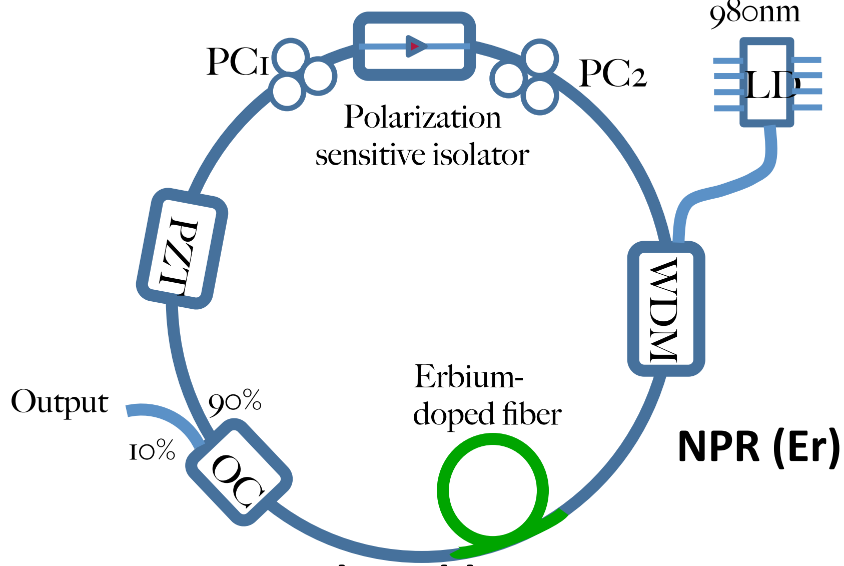
II. Photonic Microstructure Fibers

III. Comb-assisted spectroscopy: Gas-filled fibers for near-IR frequency references

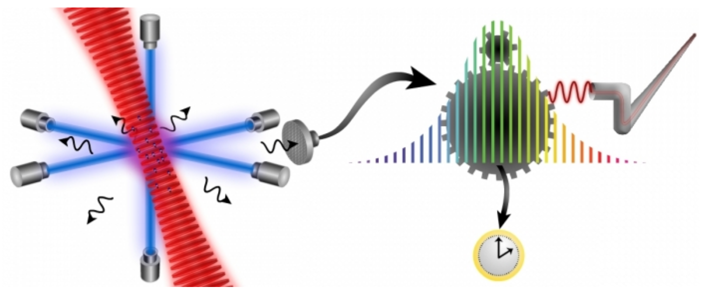
IV. Direct frequency comb spectroscopy on gas-filled fibers
- Isolating single comb tooth

Every comb needs a reference





vulnerable



Reference:

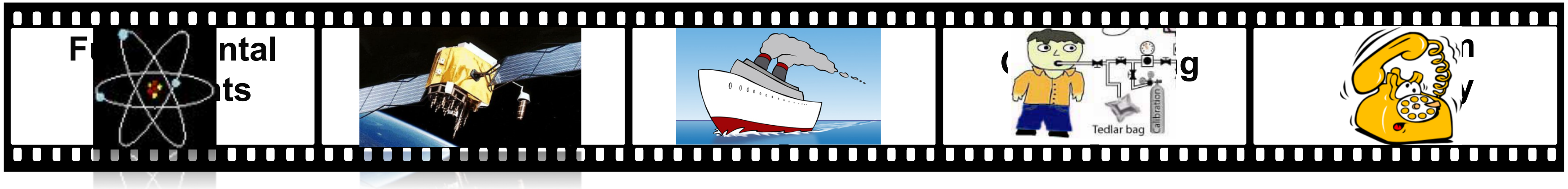
GPS-disciplined Rb: 10^{-11} @1 s, 10^{-13} accuracy
(poor short-term stability, noise multiplies)

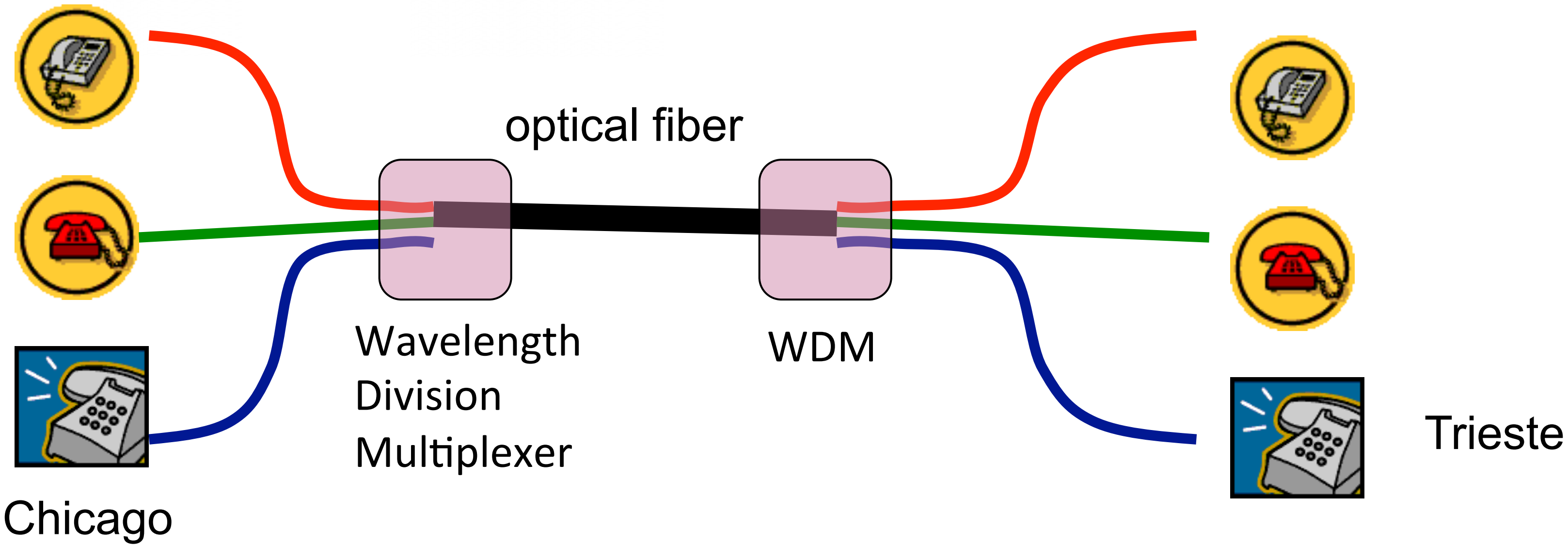
Ultracold atoms/ions: < 10^{-15} @1s (<10^{-17}) "accuracy"

Vapor cells/optical cavities 2×10^{-12} @1 s ~1 kHz (~5×10^{-12}) accuracy — **Free-space**

Gas-filled hollow fiber (our work) 10^{-11} @1 s 10 kHz (~5×10^{-11}) accuracy — **all-fiber**

Uses of portable frequency references:





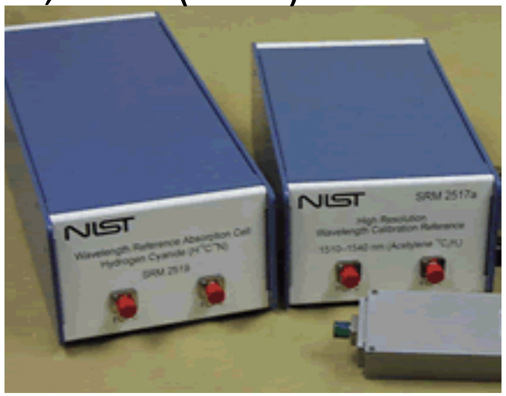
- Telecommunications industry
  - Dense wavelength division multiplexing

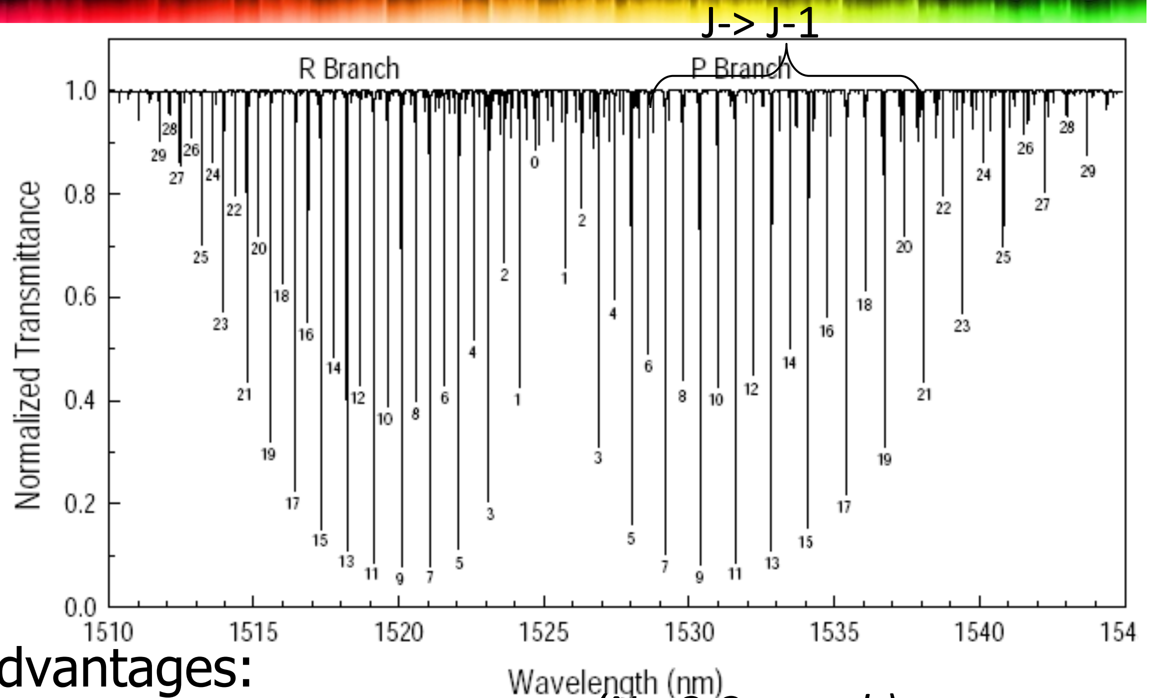
Optical Spectrum Analyzers with internal calibration.

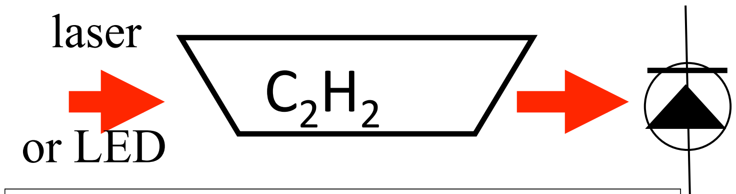
Portable acetylene frequency references: Doppler-broadened vapor cells

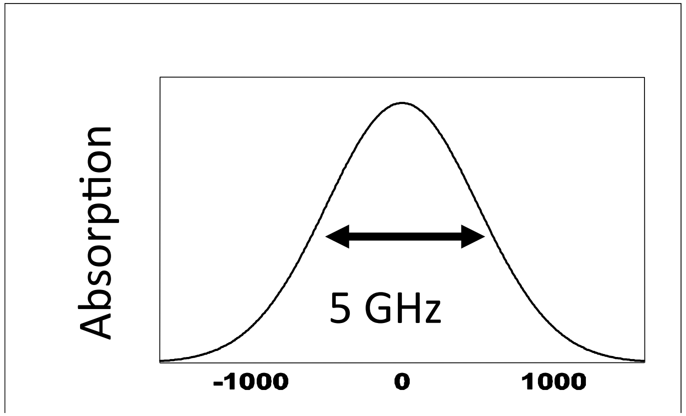
- moderate accuracy
  - (~10 MHz)

Swann and Gilbert, JOSA B, **17**, 1263 (2000)









Advantages:

Practical, stable, robust $\nu_1+\nu_3$ *(No C-C stretch)*

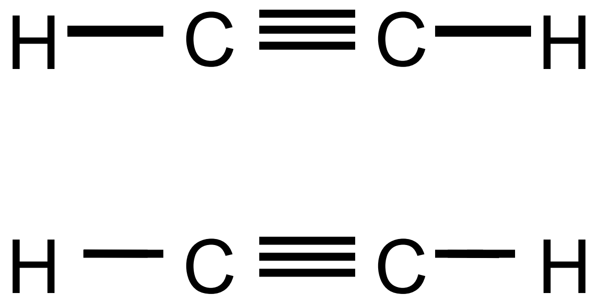
- Readily built into spectrometers

Doppler-broadening OK

- Low-power

Pressure broadening

- short interaction lengths
- width = spectrometer resolution



Portable Near-IR frequency references in 1999

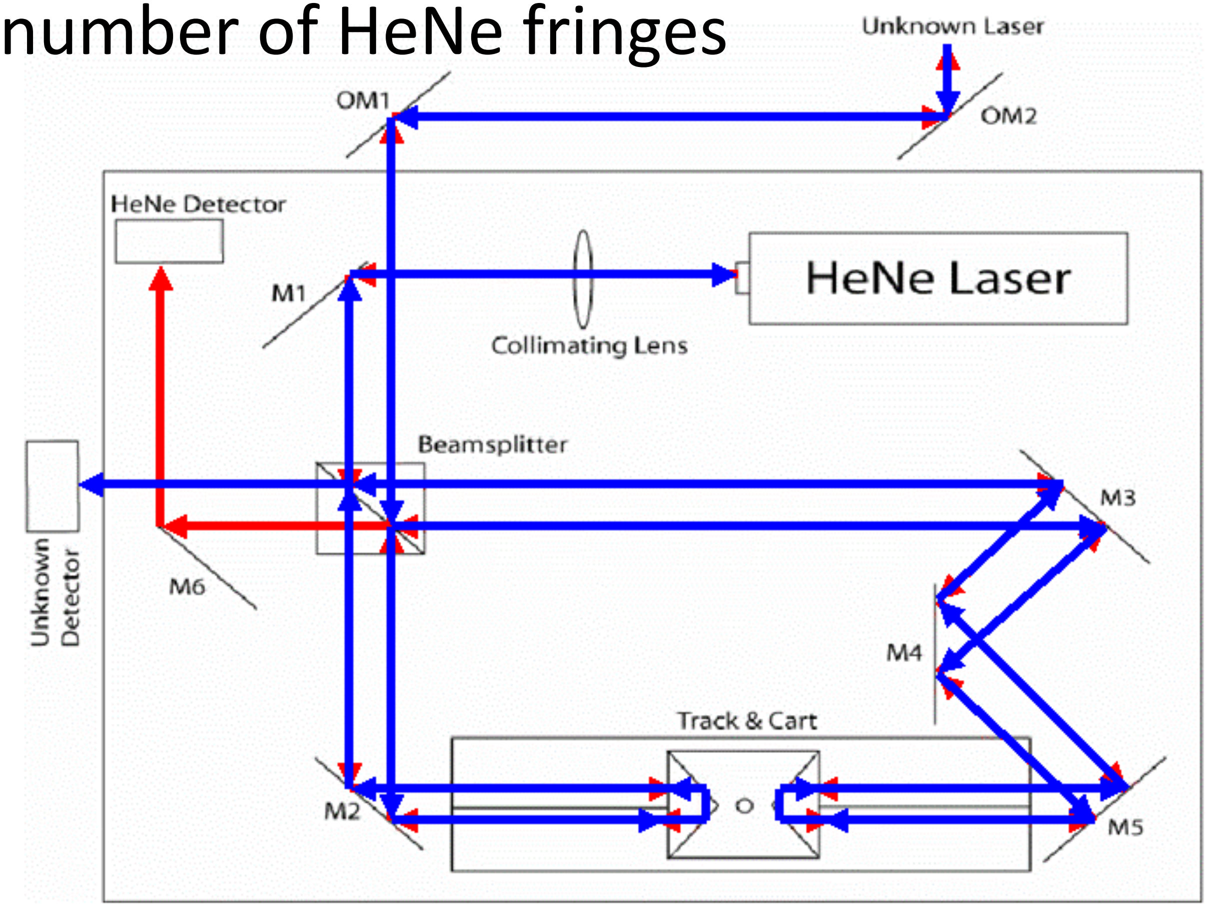
N_k = number of HeNe fringes

$$\lambda_u = (N_k/N_u) * \lambda_k$$

$$f = c/(n\ \lambda)$$

Accuracy depends on:
  cart speed,
  stability of air
    (n, index of refraction)

N_u



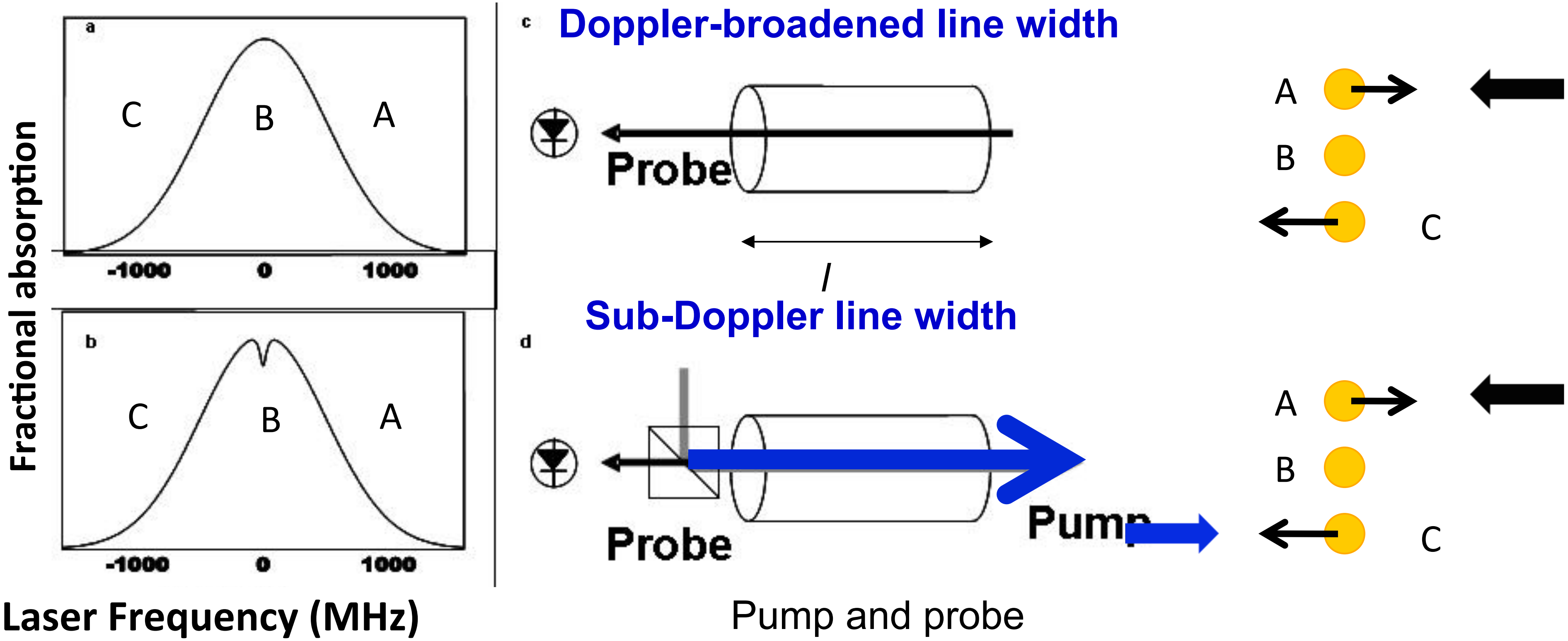
Cart Velocity v

http://hdl.handle.net/1811/30758

- NIST: Sarah Gilbert, Bill Swann

Sub-Doppler Spectroscopy: Saturated Absorption

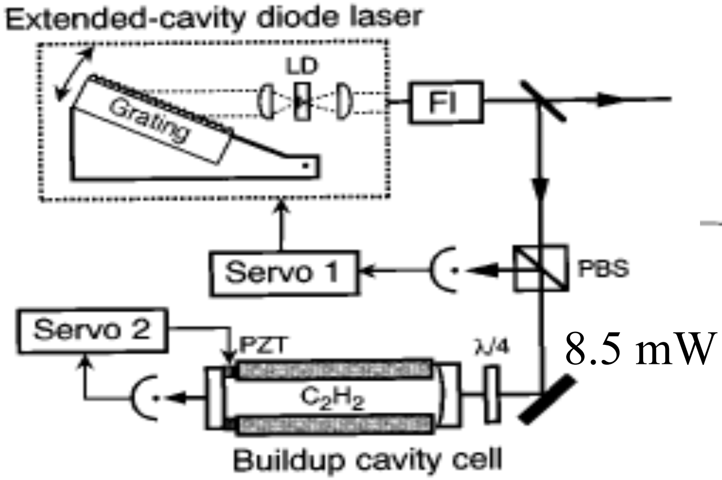
Pump burns hole in velocity distribution,
probe samples different velocity class, except when on resonance.

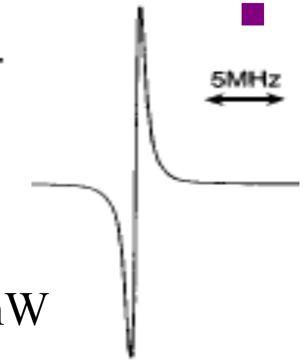


Pump and probe
at same frequency

Higher-accuracy near-IR wavelength standard: nonlinear spectroscopy

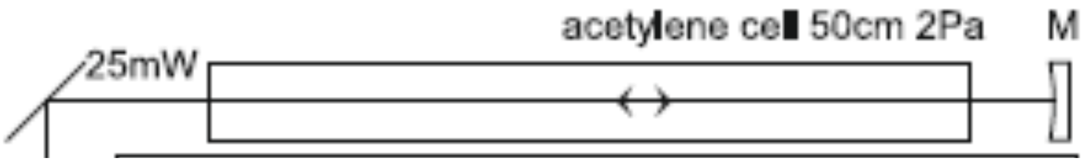
- Comité International des Poids et Measures, 2000
  - $^{13}C_2H_2$ P(16) ± 100 kHz (2000)
  - Comb-based meas. ± 2 kHz (2005)
    - Great Britain, Japan, Canada, Japan





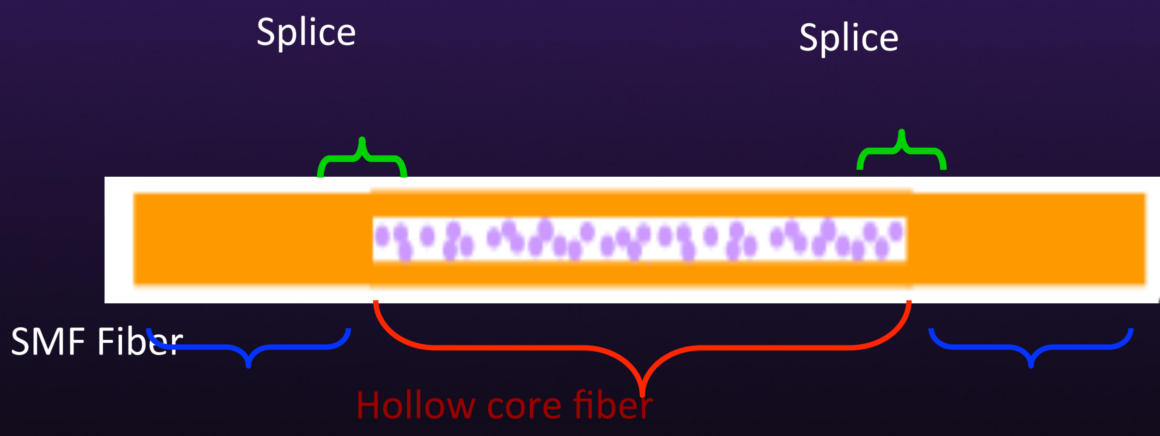
- Cavity: weak overtone transitions require
  - Long interaction length
  - High intracavity power
  - Cavity and laser locked to resonance independently

Figure from: 100 mW
K. Nakagawa, M. de Labachelerie, Y. Awaji, and M. Kourogi, JOSAB 13, 2708 (1996)



P. Balling, M. Fischer, P. Kubina, R. Holzwarth, Opt. Express 13, 9196 (2005)

Our goal: portability and accuracy



Motivation for hollow fibers:

Nonlinear Optics in Gasses

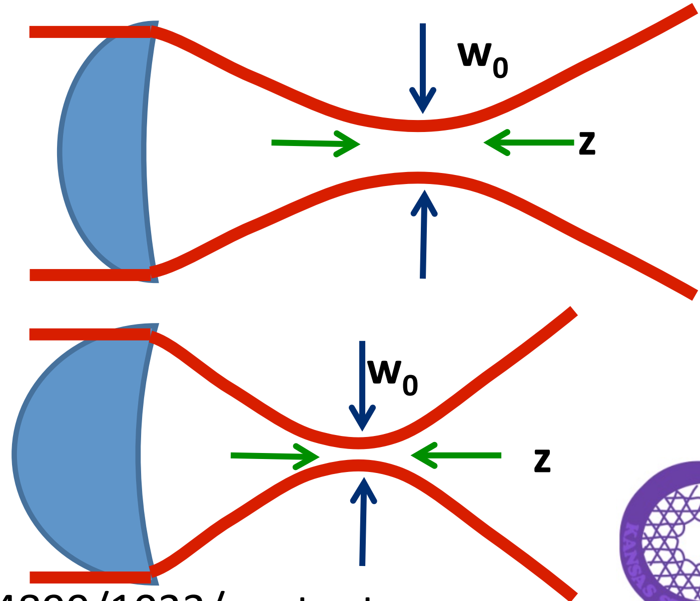
- Saturated absorption
- Optical Gain (population inversion)

Require:

- High Intensities
- Long interaction lengths, and/or high densities

Free Space Limitation:

- Diffraction!
  - Tight focus = fast divergence
  - $w_o \sim f \quad z \sim f^2$

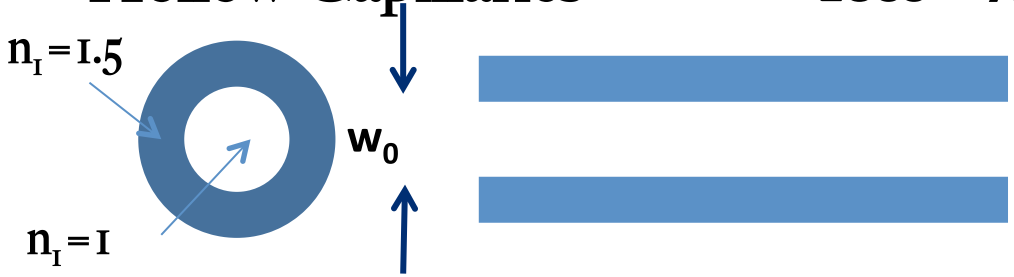


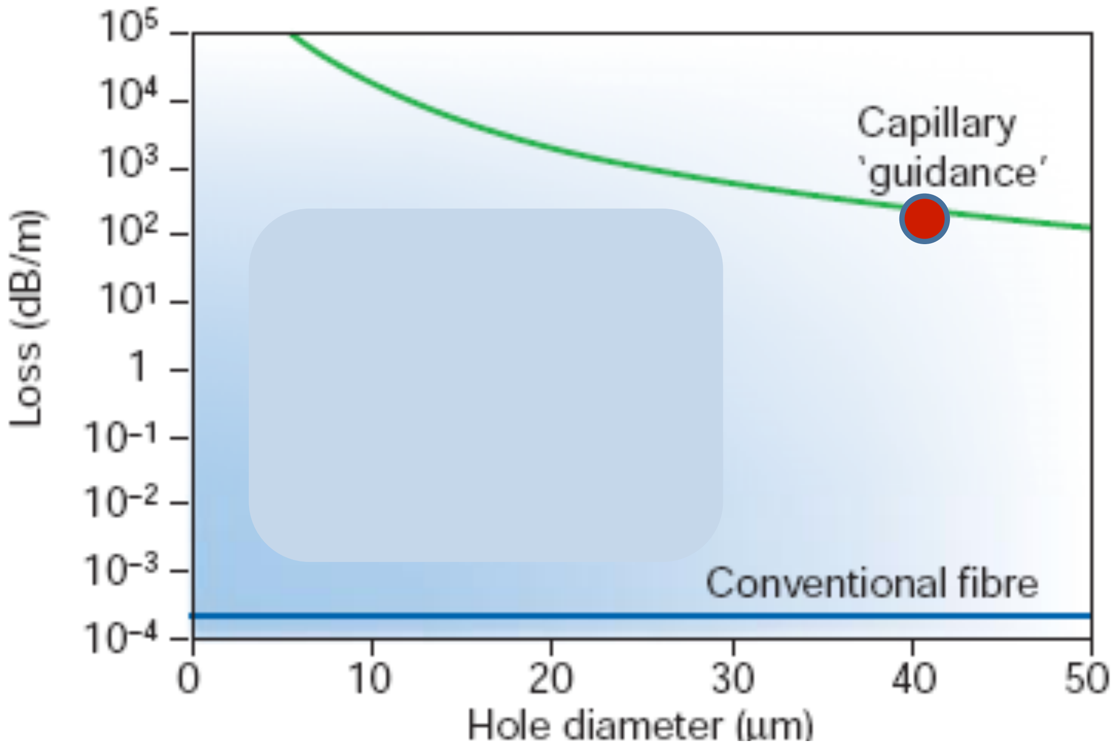
http://www.newport.com/Gaussian-Beam-Optics/144899/1033/content.aspx

Hollow dielectric Waveguides:

Hollow Capillaries

Loss ~ λ^2/w_0^3





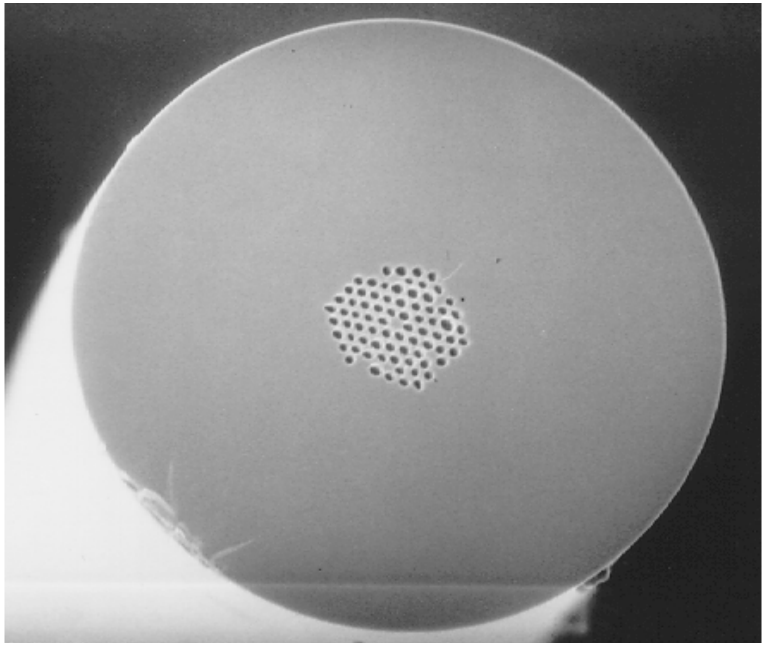
Marcatili and Schmeltzer, Bell System Technical Journal, **43**, (1964), pp. 1783-1809

"Hence, dielectric materials do not seem suitable for use in hollow circular waveguides for long distance optical transmission because of the high loss introduces by even mild curvature… **very attractive as guiding media for gaseous amplifiers and oscillators** …."

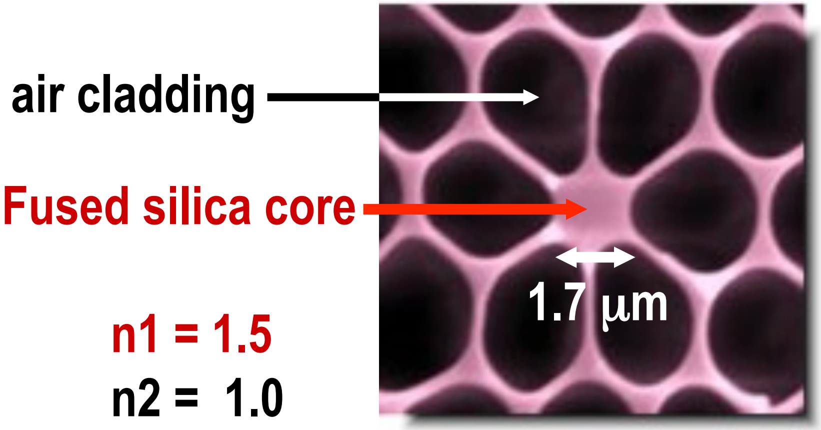
6.2 cm attenuation length at 780 nm for 40 μm dia.

Knight, J.C., *Photonic crystal fibers.* Nature, 2003. **424**: p. 847.

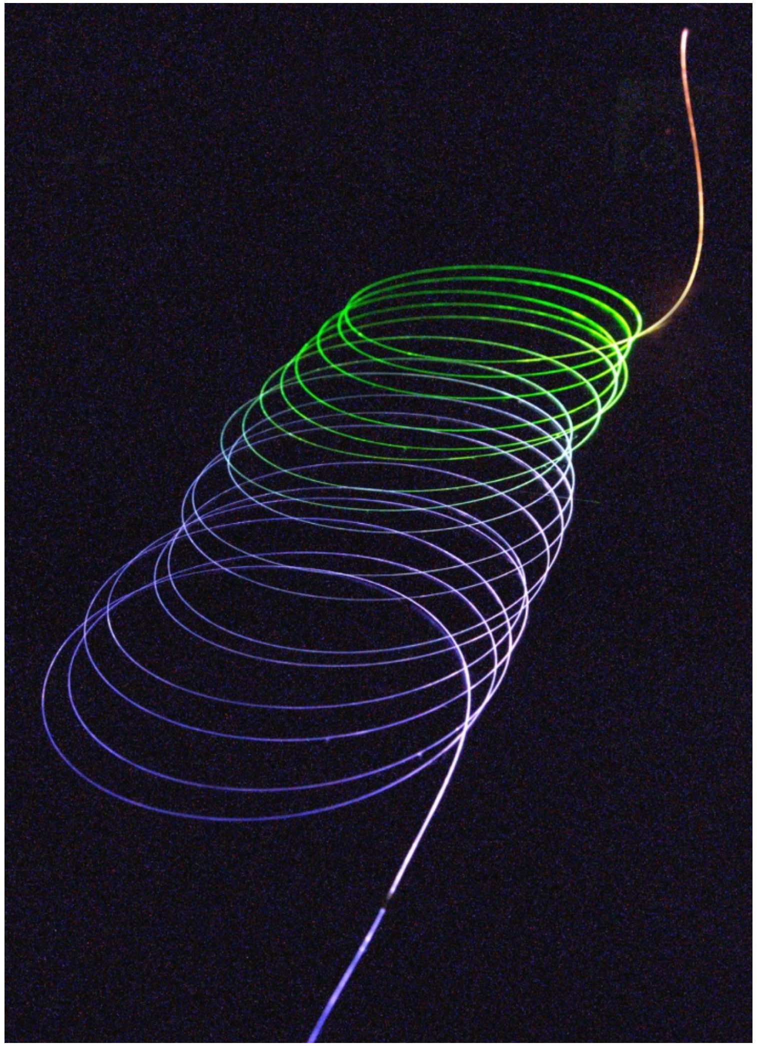
1999-2000: Honeycomb Microstructure Optical Fiber – enabling a Nobel prize



J. Ranka, R. Windeler, A. Stentz, Opt. Lett. **25**, 25 (2000).



n1 = 1.5
n2 = 1.0

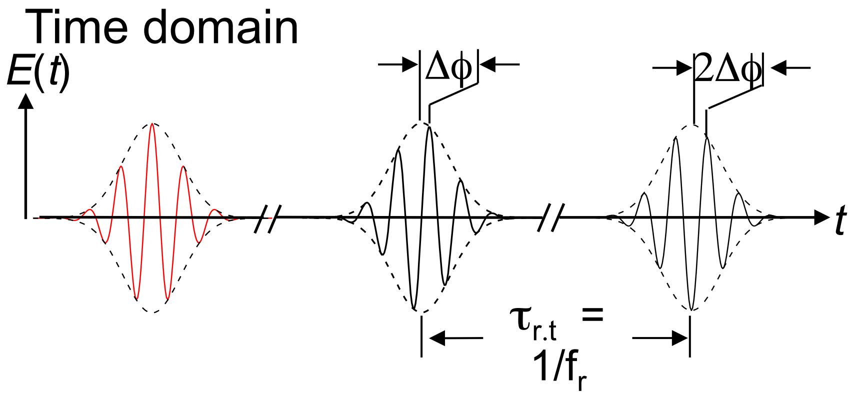


courtesy of Jinendra Ranka

Lucent Technologies
Bell Labs Innovations

ofs
Leading Optical Innovations

Supercontinuum generation for f_o stabilization

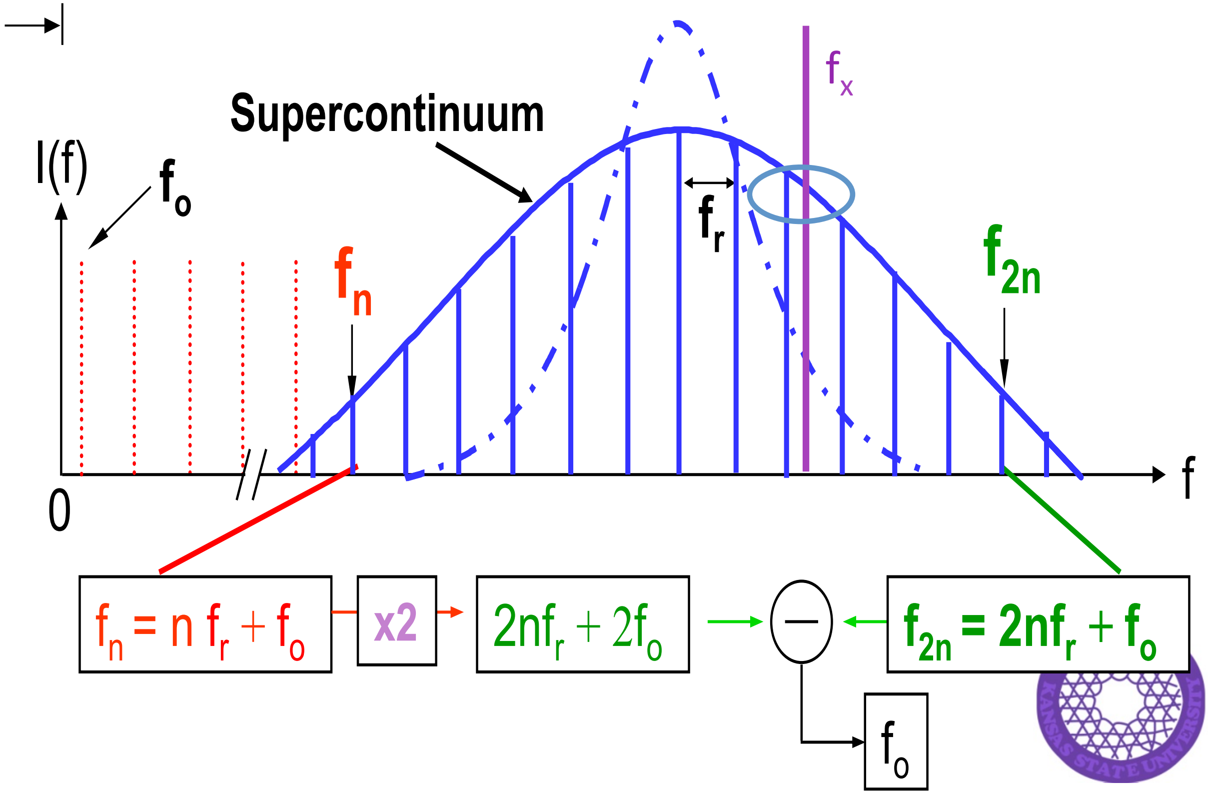


D. J. Jones *et al.*, Science 288, 635 (2000)

S. Diddams *et al.*, Science, vol. 293 (2001)

"Self-Referenced"
Optical Frequency Comb

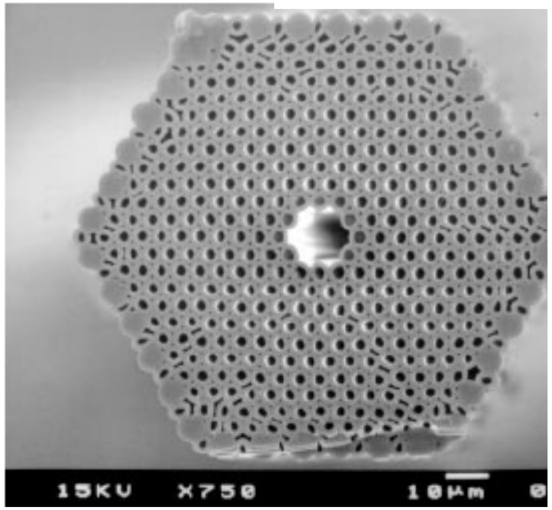
Beat note gives f_x



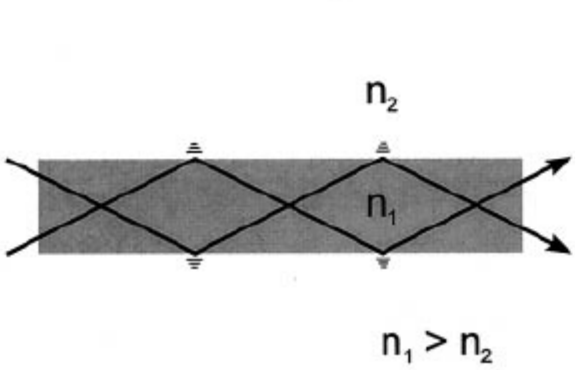
Single-Mode Photonic Band Gap Guidance of Light in Air

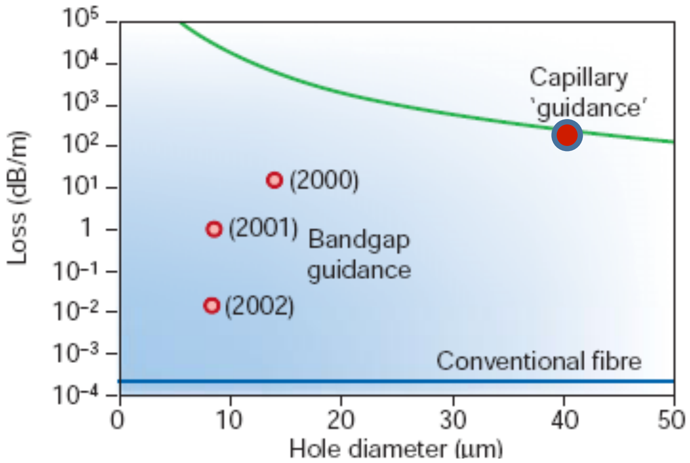
R. F. Cregan,[1] B. J. Mangan,[1] J. C. Knight,[1] T. A. Birks,[1]
P. St. J. Russell,[1*] P. J. Roberts,[2] D. C. Allan[3]

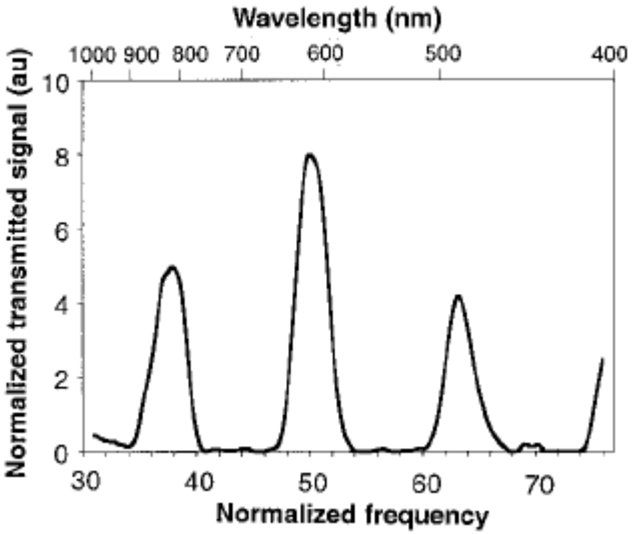
A



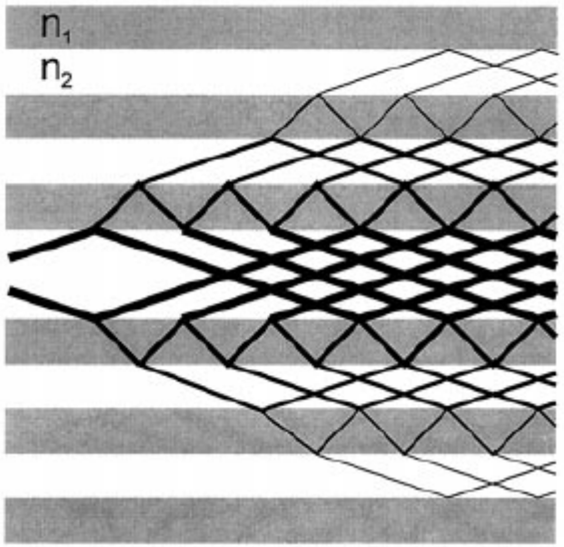
A Conventional TIR guidance







C Bragg PBG guidance

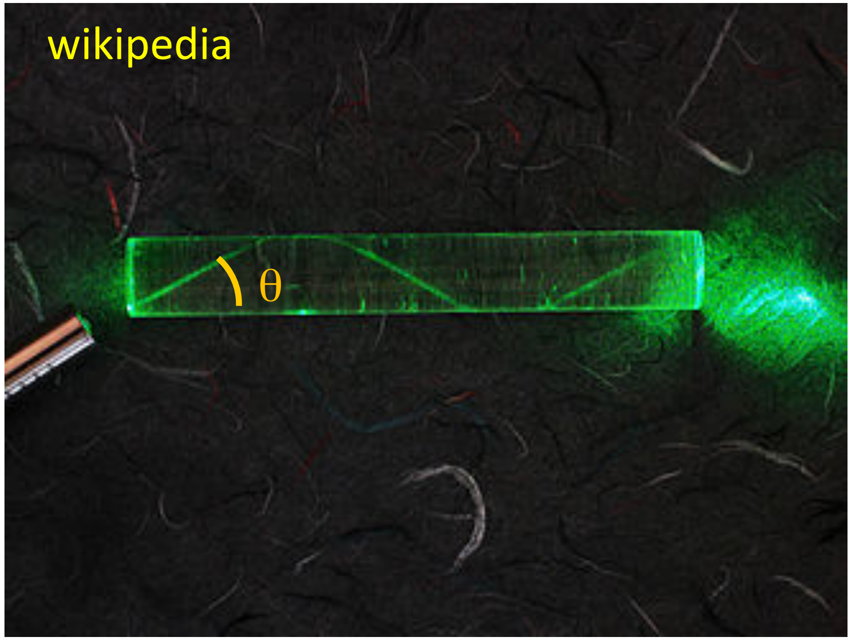


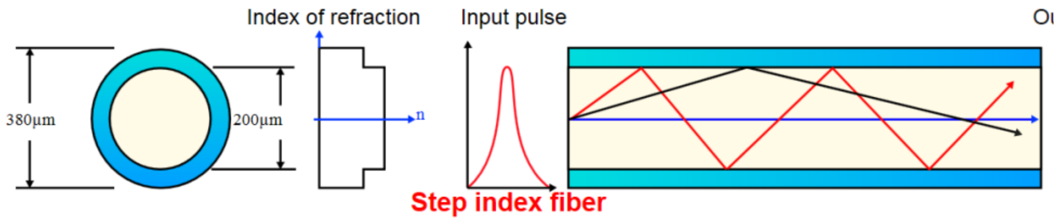
SCIENCE VOL 285 3 SEPTEMBER 1999

Knight, J.C., *Photonic crystal fibers.* Nature, 2003. **424**: p. 847.

6.2 cm attenuation length at 780 nm for 40 µm dia.

Fiber propagation





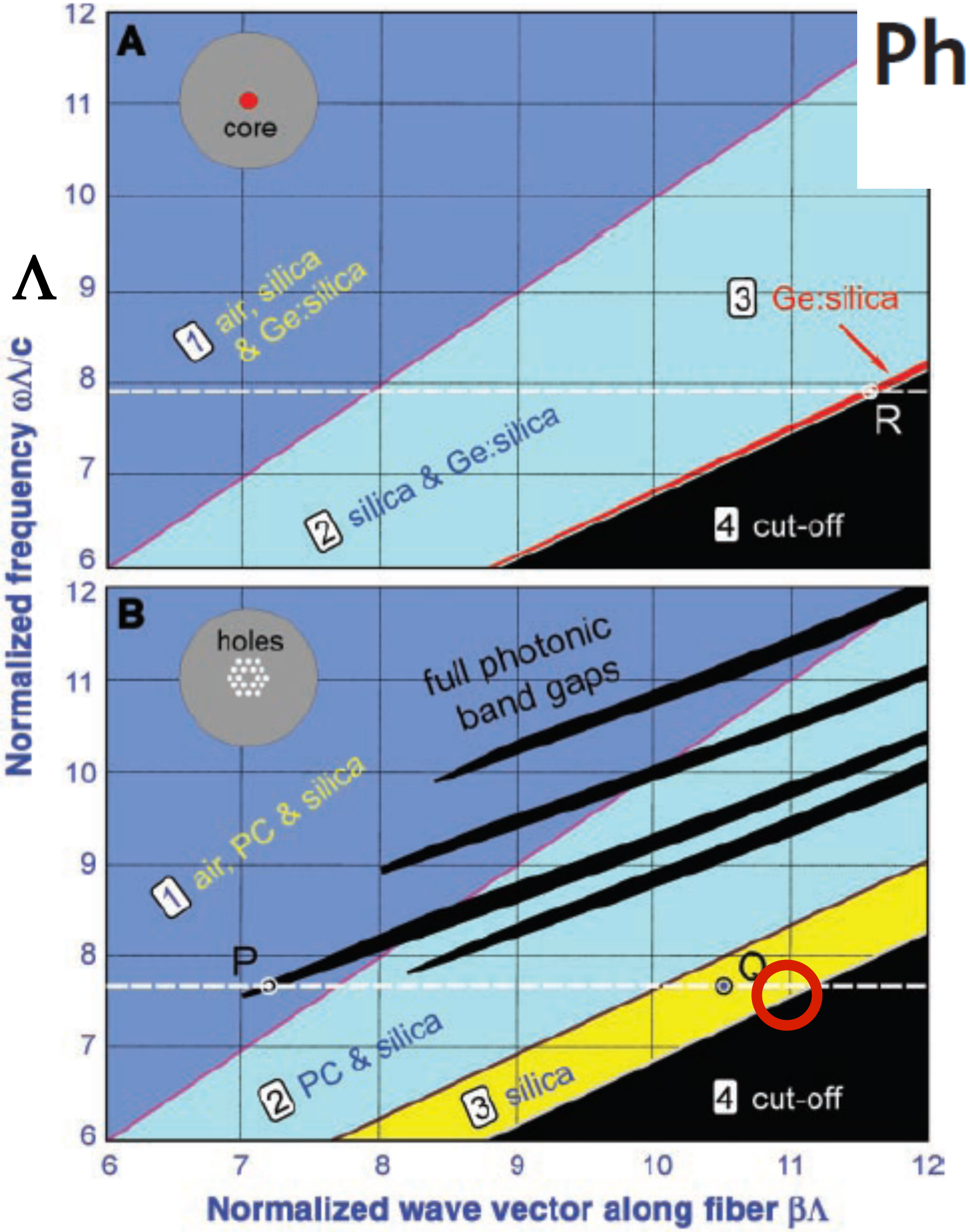
Vacuum wavelength λ_0, wavevector $k_o = 2\pi/\lambda_0$ $(= \omega/c)$

In medium with index n, $\lambda_n = \lambda_0/n$

- $\lambda_{eff} = \lambda_n \cos\theta$
- $\beta = k_z = 2\pi/\lambda_{eff}$;
- for higher-order modes, λ_{eff} smaller, β bigger

How PBG fibers work

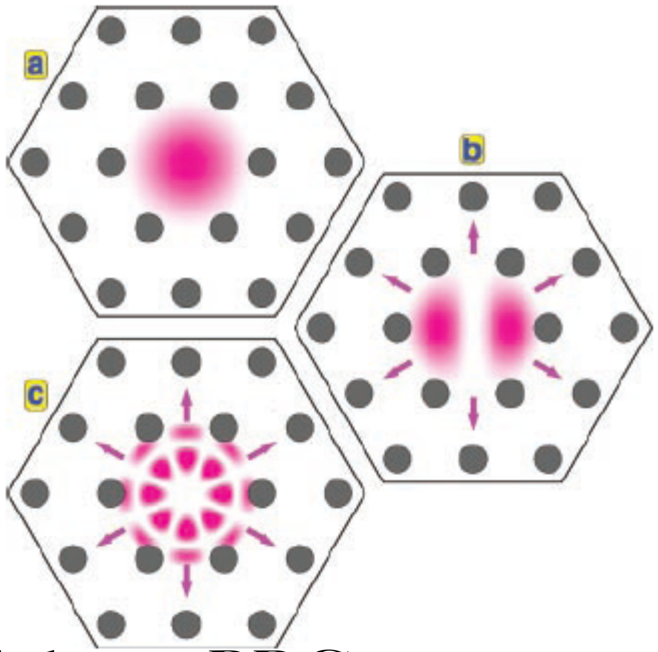
$k_0 \Lambda$



Photonic Crystal Fibers

Philip Russell

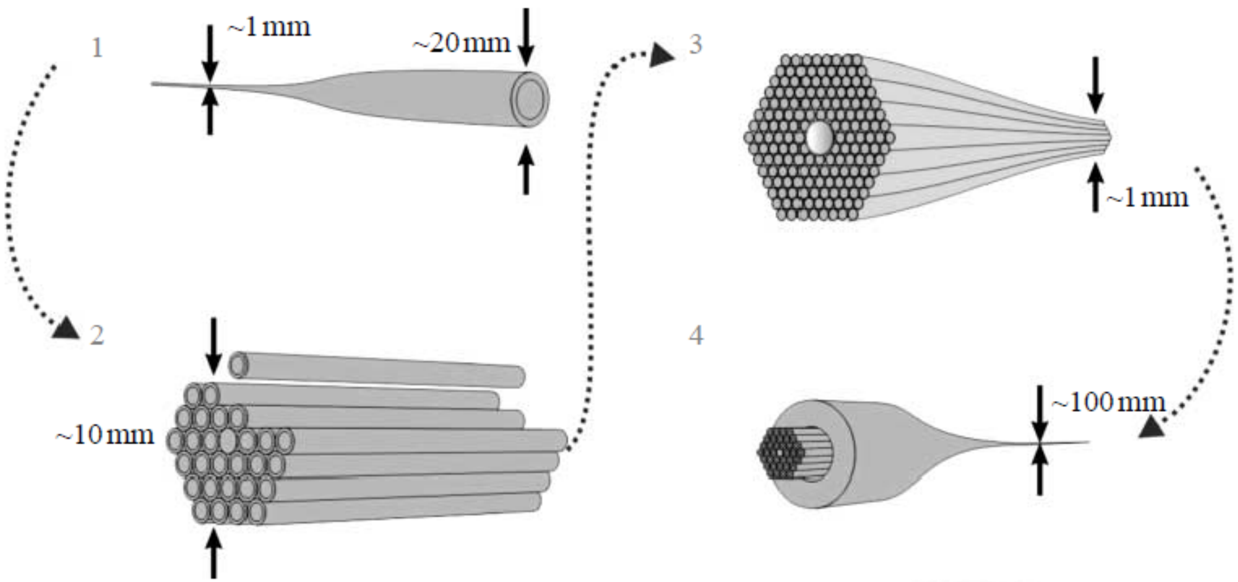
17 JANUARY 2003 VOL 299 SCIENCE

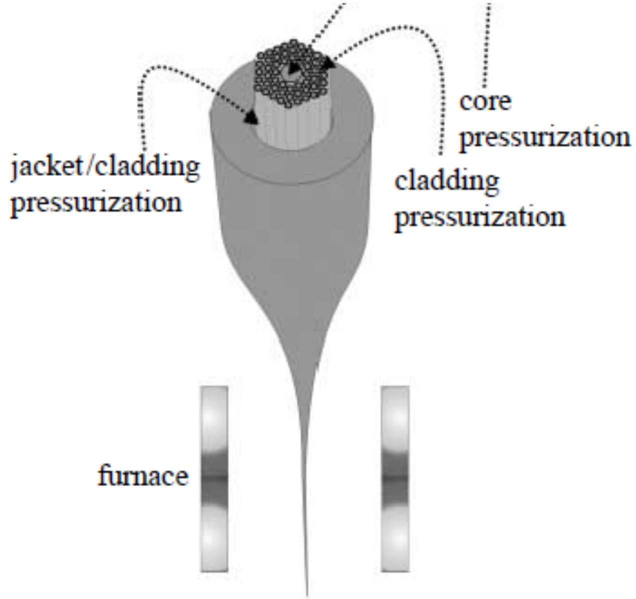


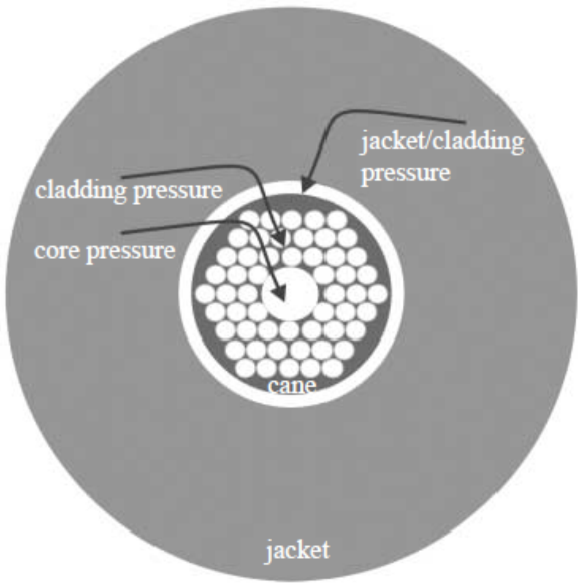
Solid-core PBG
"endlessly single-mode"

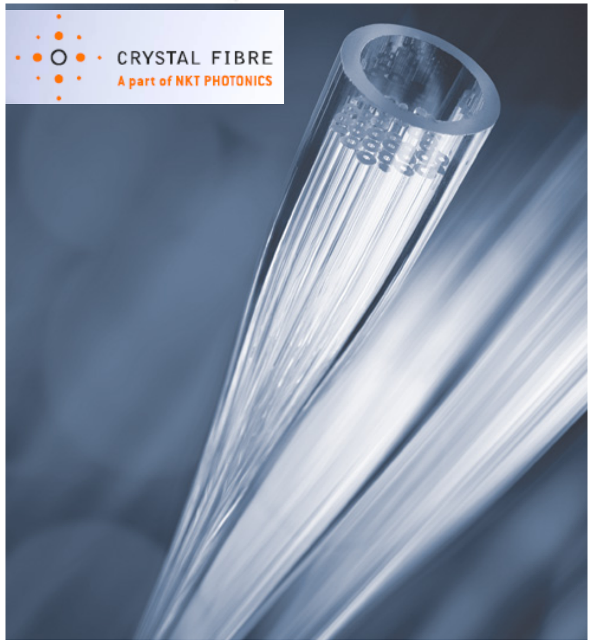
N = 1.5, 11/1.5 = 7.3

Fabrication, Pressurization



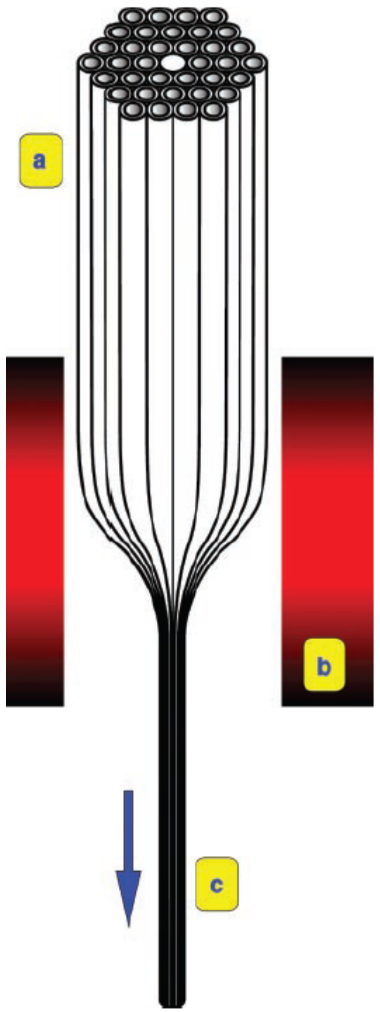






F. Benabid, "Hollow – core photonic band gap fibre: new light guidance for new science and technology," Philos. Trans. R. Soc. London, Ser. A **364(1849), 3439–3462 (2006).**

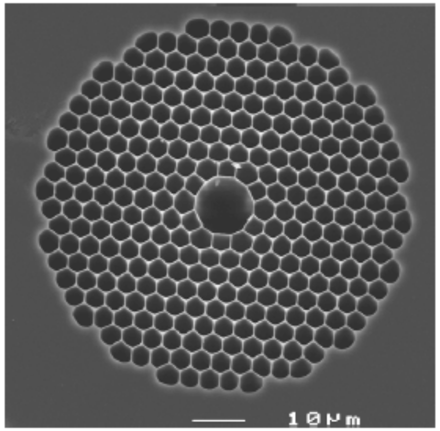
Fabrication

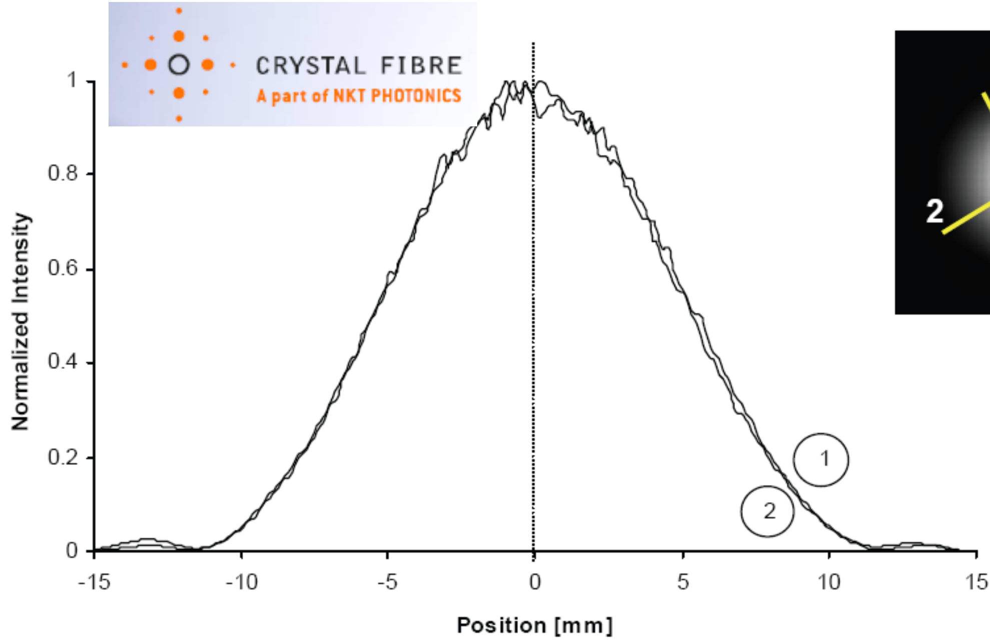


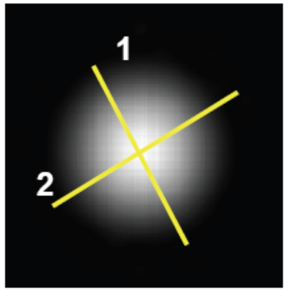
William Wadsworth (left) and Sam Bateman finish a photonic crystal fiber stack.

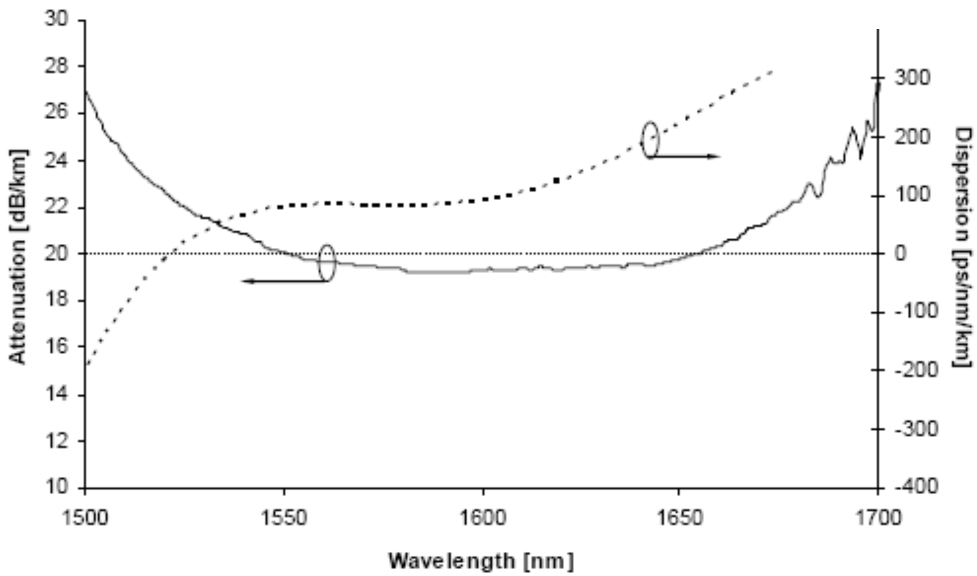
Photonic Bandgap Fibers

20 μm core size









- Only 3% of power in cladding.

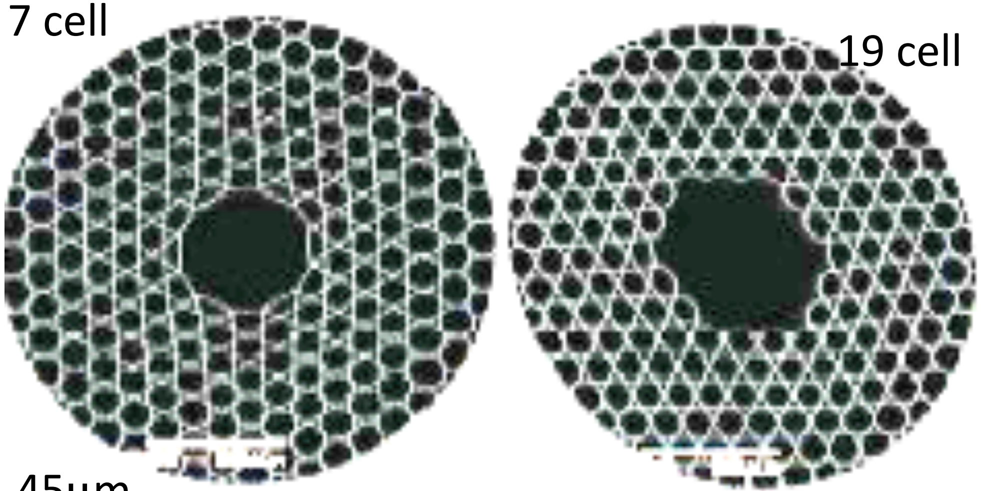
3574 OPTICS LETTERS / Vol. 31, No. 24 / December 15, 2006

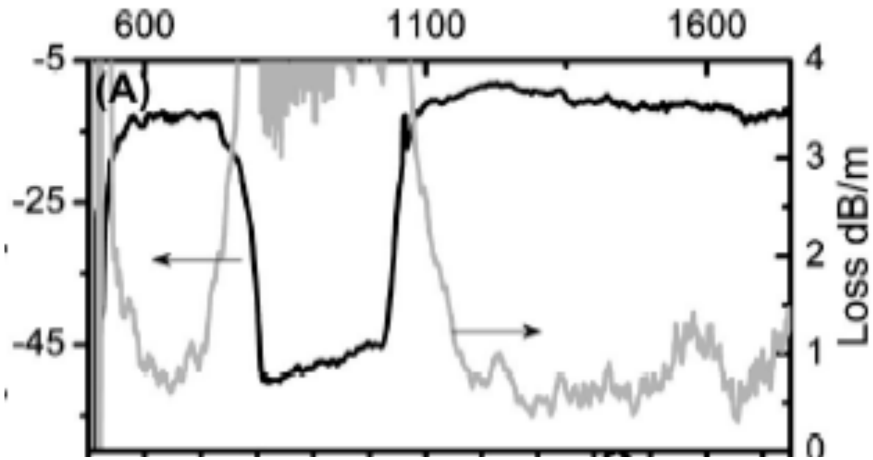
Kagome fiber

Large-pitch kagome-structured hollow-core photonic crystal fiber

F. Couny, F. Benabid, and P. S. Light

Centre for Photonics and Photonic Materials, University of Bath, Bath BA2 7AY, UK





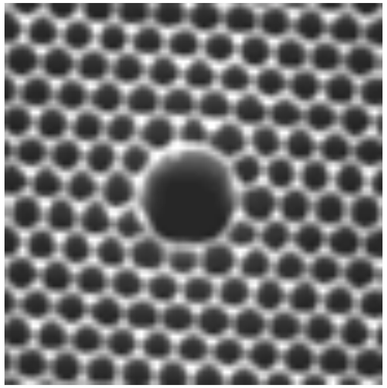
- Advantages:
  - larger core for narrower lines
  - flatter backgrounds – reduced surface modes
- Potential Disadvantage: multi-mode

http://www.fz-juelich.de/iff/e_news_09-02-2007

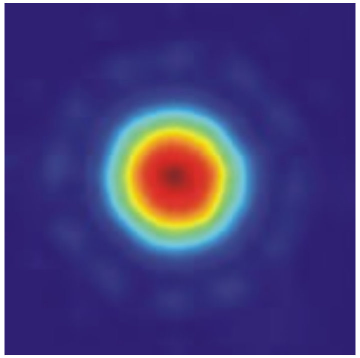
- Made by accident, full power not initially realized!

Surface Modes

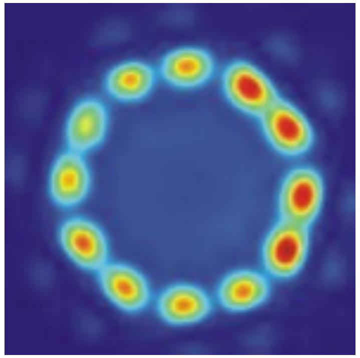
PCF

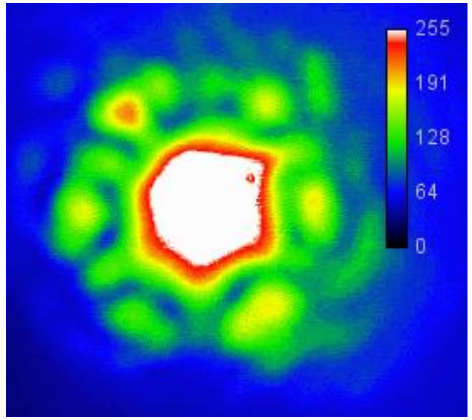


Core Mode



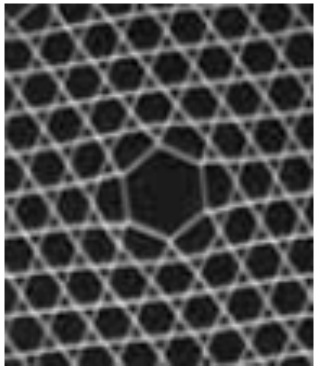
Surface Mode



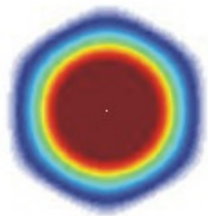


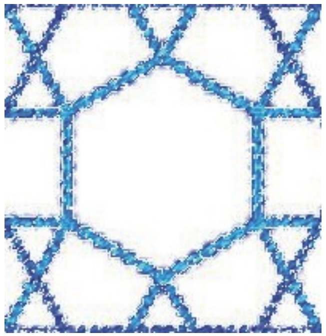
Smith, West, et al. Nature 2003

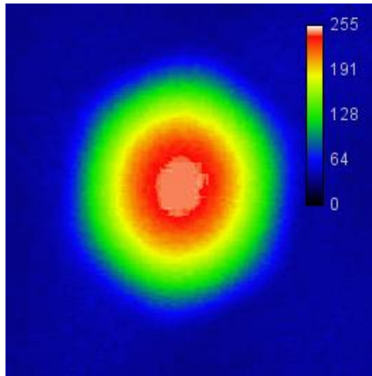
- Coupling between core modes and surface modes in PCF cause oscillatory transmission dependence



Kagome



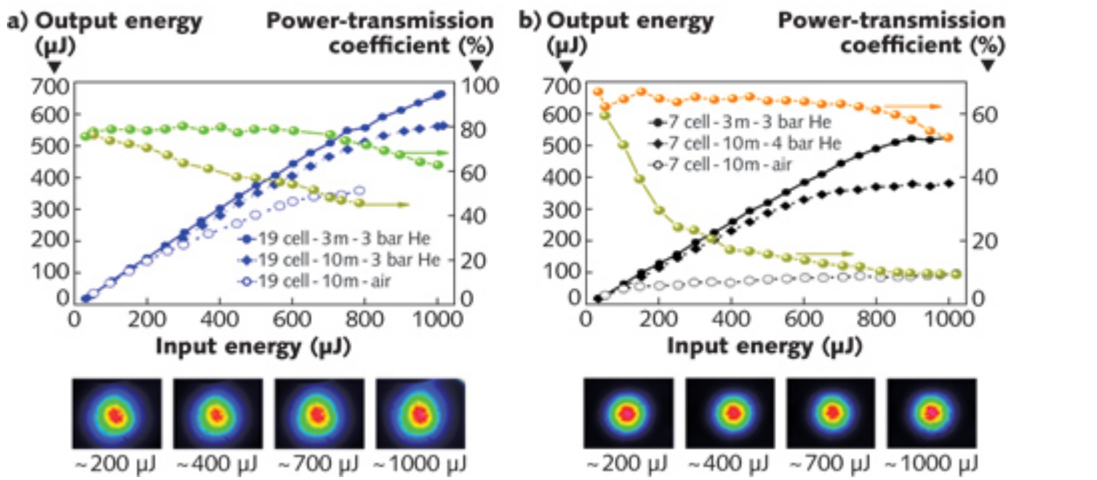


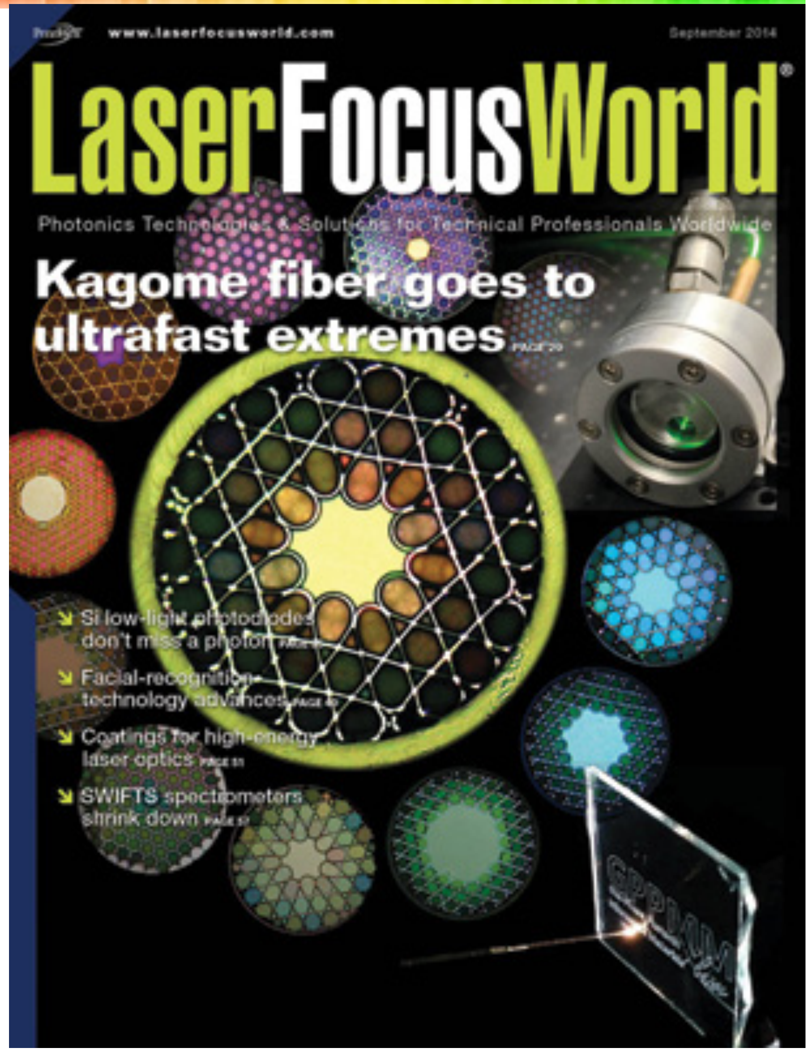


UNIVERSITY OF BATH

F. Couny, *et al.* Science 2007

Hypocycloid fibers

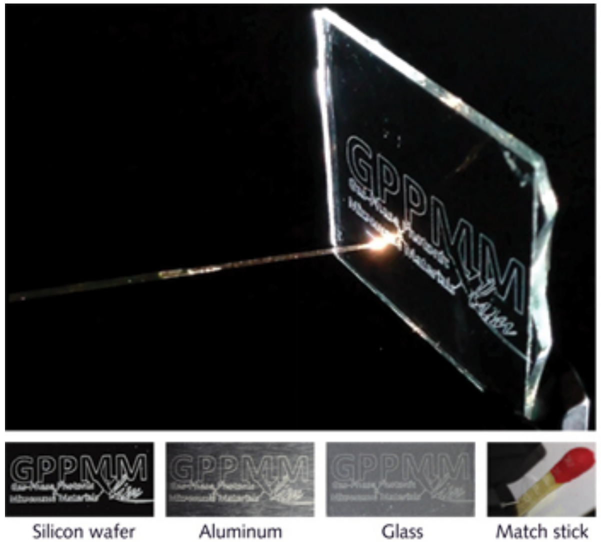




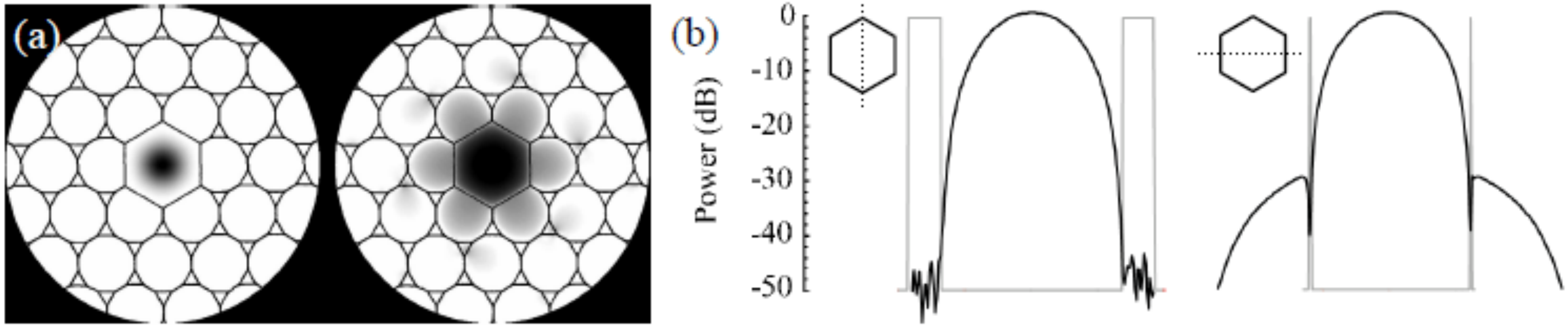
Loss ~30dB/km
(SMF .2 dB/km)
Ultrashort pulse delivery

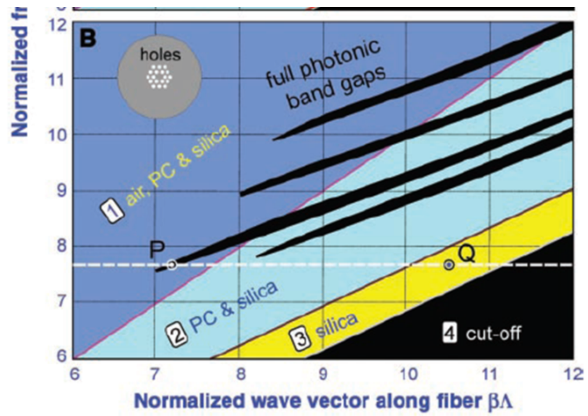
<49 fs, ~ 1 mJ input pulses, 0.7 mJ transmitted

Fluence >> damage thresh of fused silica



Guiding mechanism: frustrated coupling





- Factors determining coupling of core-> cladding modes:
  - Mismatch in propagation constant ($\Delta\beta$)
  - Spatial overlap of two modes
    - Overlap with solid part of microstructure
    - Perturbations in microstructure

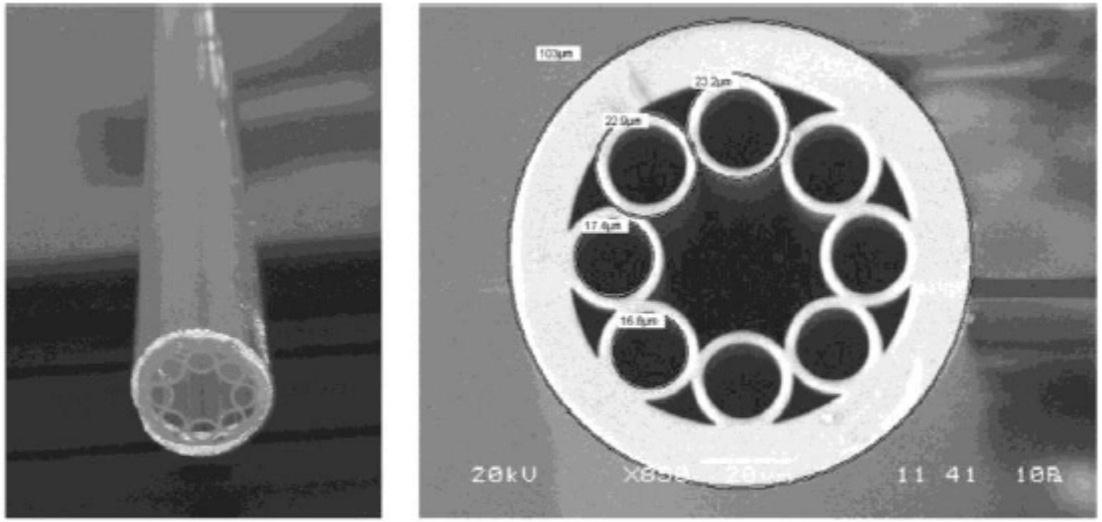
A. Argyros, and J. Pla, “Hollow-core polymer fibres with a kagome lattice: potential for transmission in the infrared,” Opt. Express **15(12), 7713–7719 (2007), http://www.opticsinfobase.org/oe/abstract.cfm?URI=oe-15-12-7713.**

Demonstration of a waveguide regime for a silica hollow - core microstructured optical fiber with a negative curvature of the core boundary in the spectral region > 3.5 μm

Andrey D. Pryamikov,* Alexander S. Biriukov, Alexey F. Kosolapov, Victor G. Plotnichenko, Sergei L. Semjonov, and Evgeny M. Dianov

Fiber Optics Research Center of Russian Academy of Sciences, 38 Vavilov street, Moscow, 119333, Russia

**pryamikov@fo.gpi.ru*



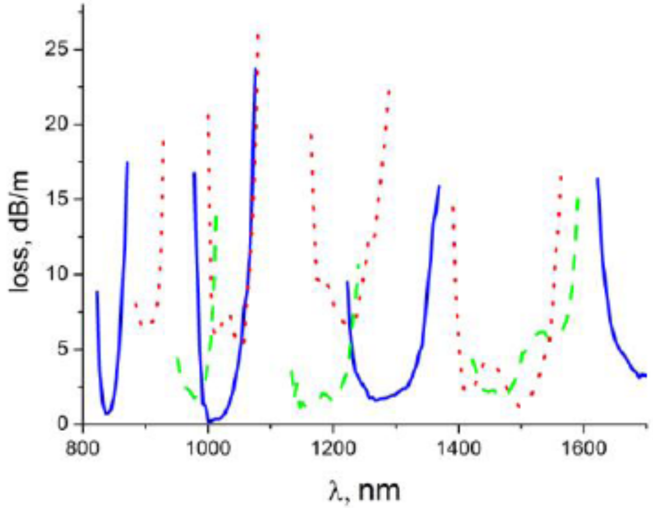
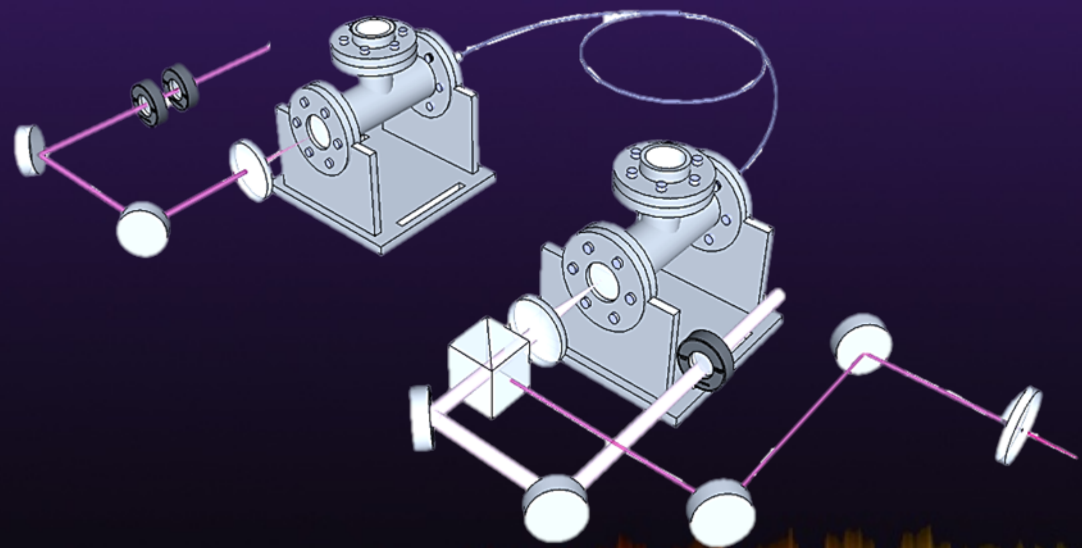
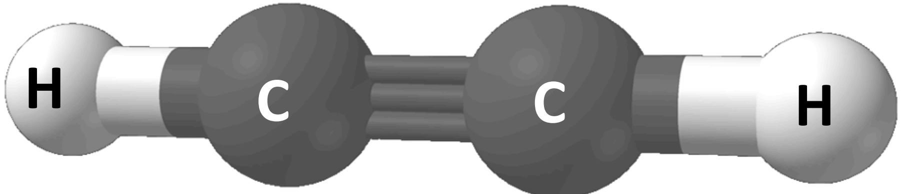


Fig. 4. The preform (left) and cross section of HC MOF (right) with the cladding consisting of eight capillaries and D_{core} ≈36 μm.

Fiber-based frequency references

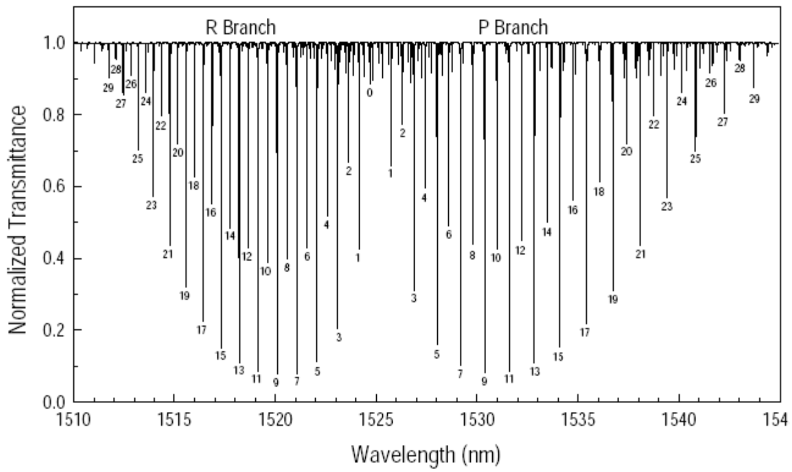


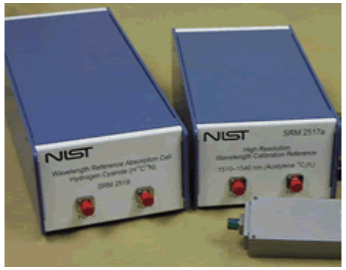
acetylene references



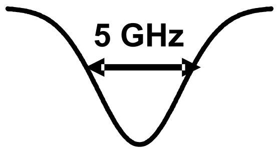
wikipedia.org

– NIST pressure-broadened cells: cheap, lower accuracy



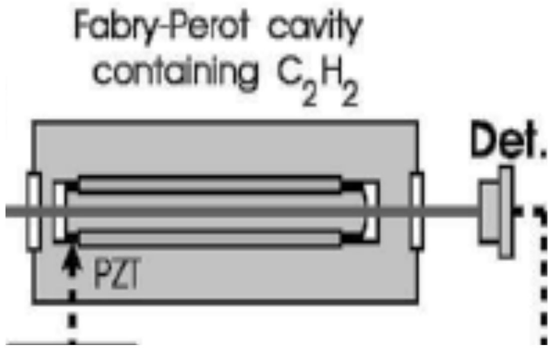


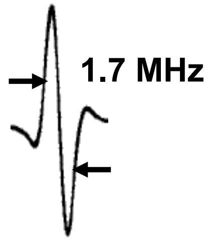
Moderate accuracy (±100 MHz)



Portable robust

W.C. Swann NIST (2000)





Accurate (1kHz)

A.A. Madej INMS (2006)

– Sub Doppler free-space: Power build-up cavities and vapor cells

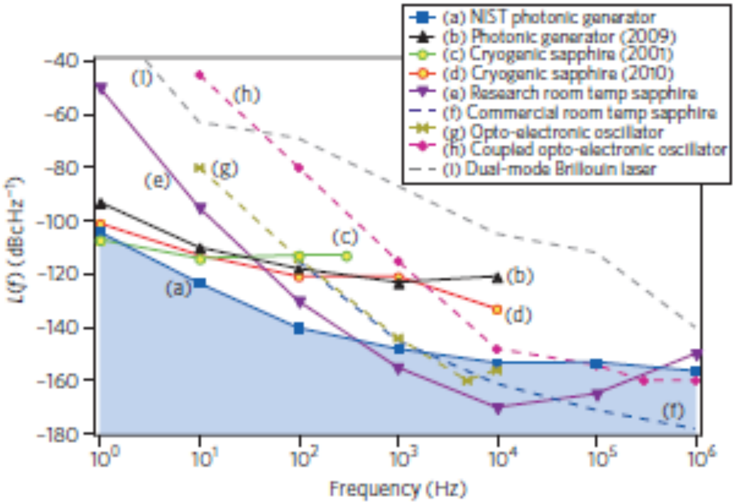
  • More complex, bulky;

Motivation: Best microwaves come from optical references

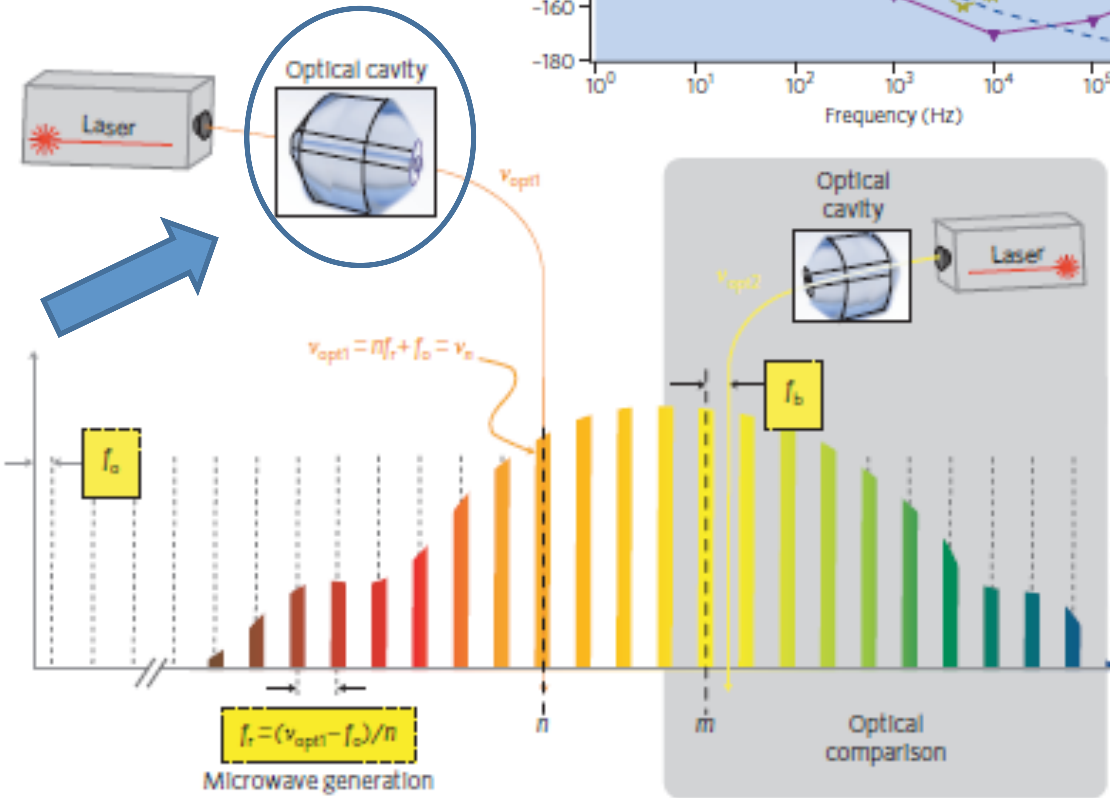
Generation of ultrastable microwaves via optical frequency division

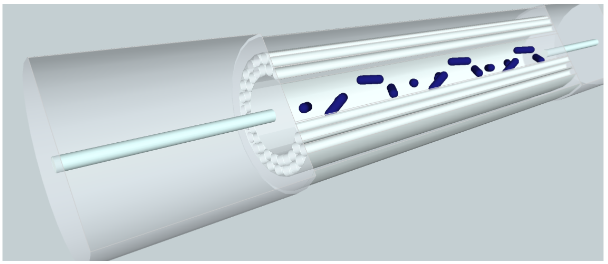
T. M. Fortier*, M. S. Kirchner, F. Quinlan, J. Taylor, J. C. Bergquist, T. Rosenband, N. Lemke, A. Ludlow, Y. Jiang, C. W. Oates and S. A. Diddams*

NATURE PHOTONICS | VOL 5 | JULY 2011 |



- 10 GHz signal
  - <8x10^{-16} at 1 s



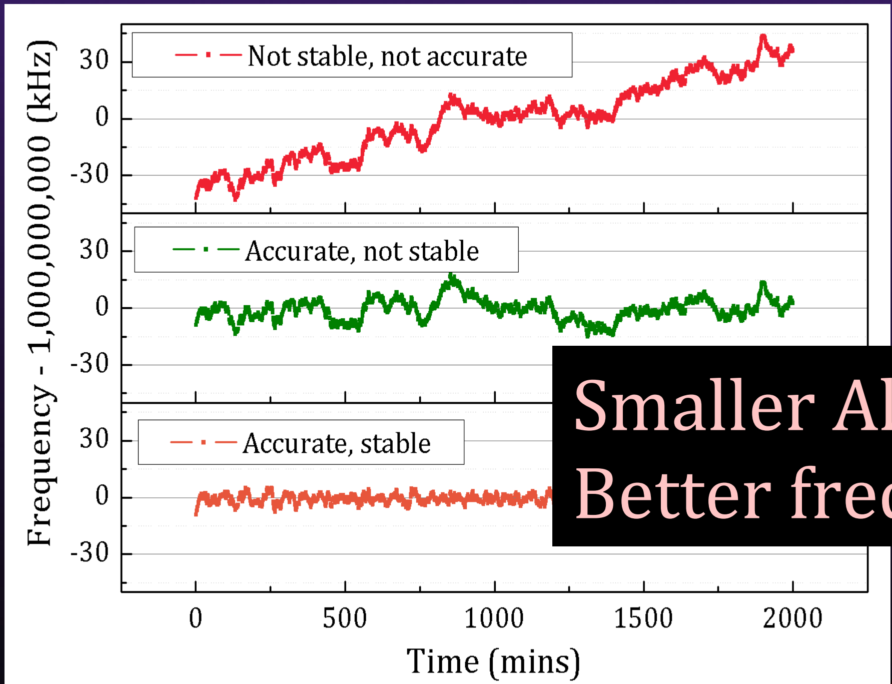


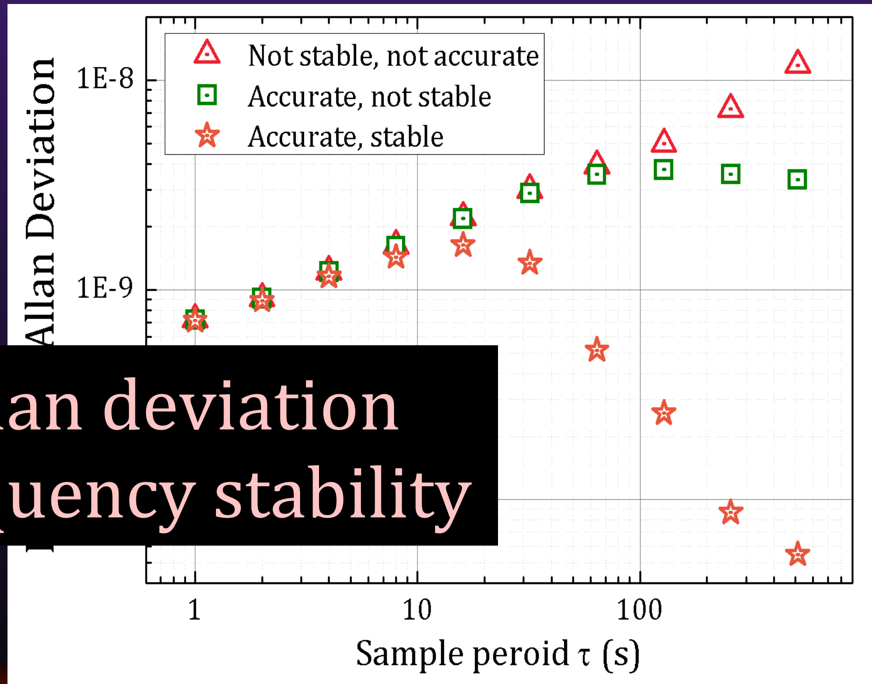
Allan deviation

Allan variance : Two-sample variance to measure the frequency stability in clocks, oscillators and amplifiers.

Allan deviation: $\sqrt{\text{Allan variance}}$, measure the point to point fluctuations.

$$\sigma_y(\tau) = \sqrt{\frac{1}{2(M-1)}\sum_{i=1}^{M-1}(y_{i+1}-y_i)^2}$$



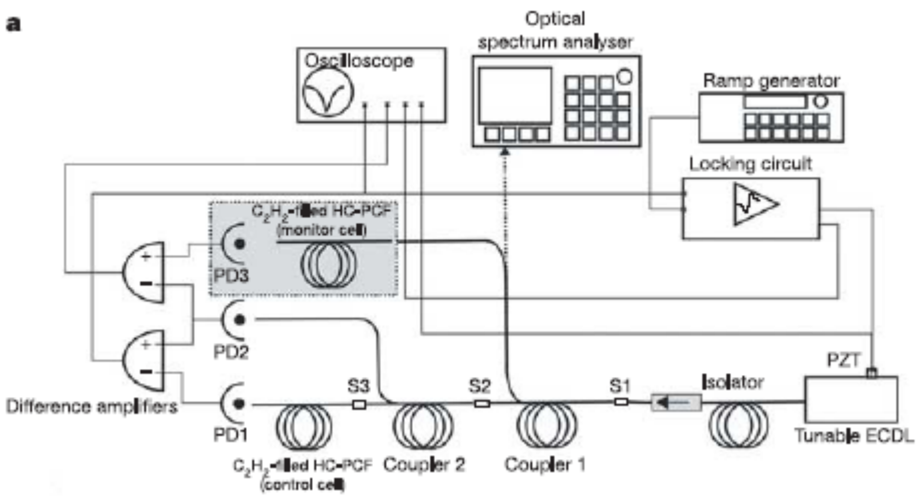


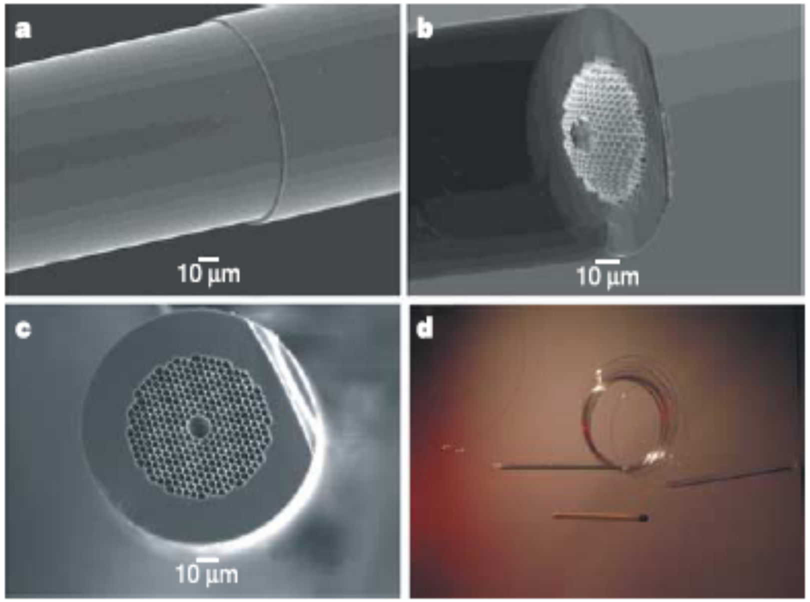
Smaller Allan deviation
Better frequency stability

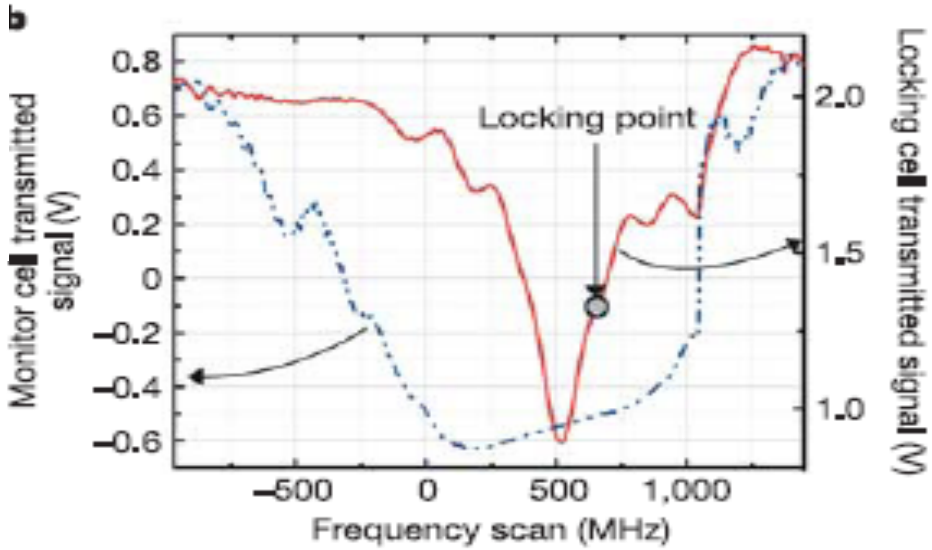
Early PBG fiber reference

Compact, stable and efficient all-fibre gas cells using hollow-core photonic crystal fibres

F. Benabid, F. Couny, J. C. Knight, T. A. Birks & P. St J. Russell

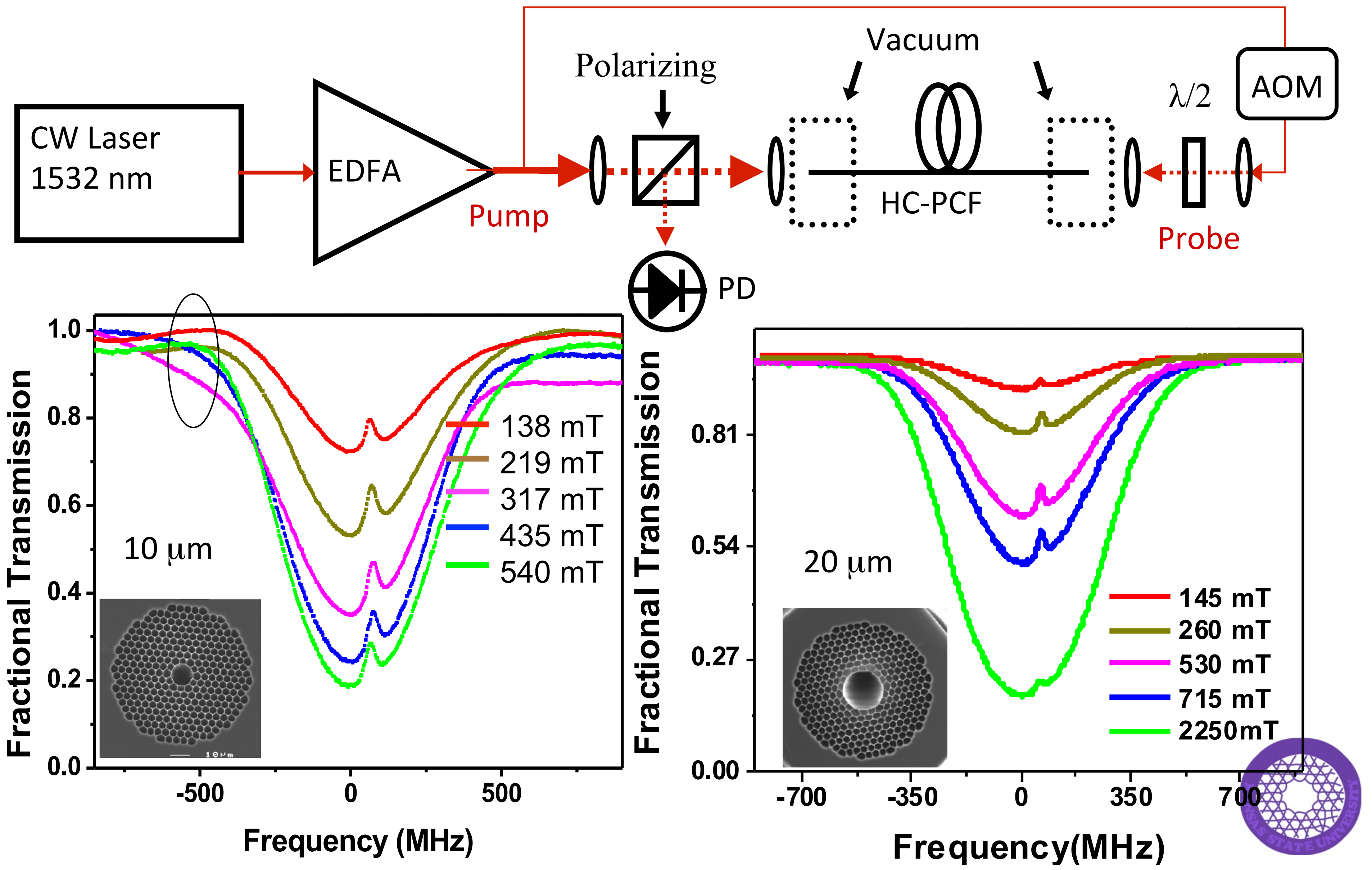






In-loop noise, ~10^{-11}/Hz $^{-1/2}$
Odd lineshape
Doppler-Broadened

Saturated Absorption spectroscopy in PCF



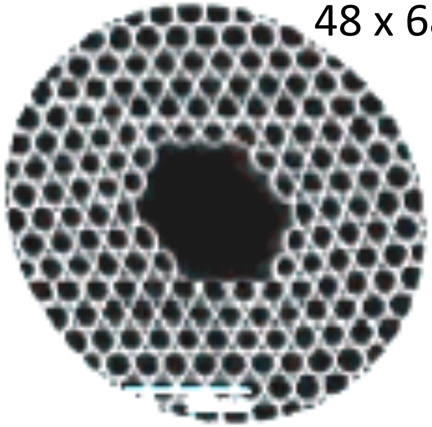
Sub-Doppler Widths in Kagome

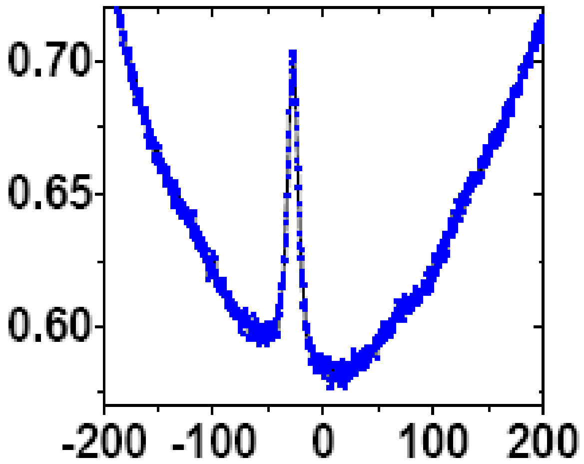
3574 OPTICS LETTERS / Vol. 31, No. 24 / December 15, 2006

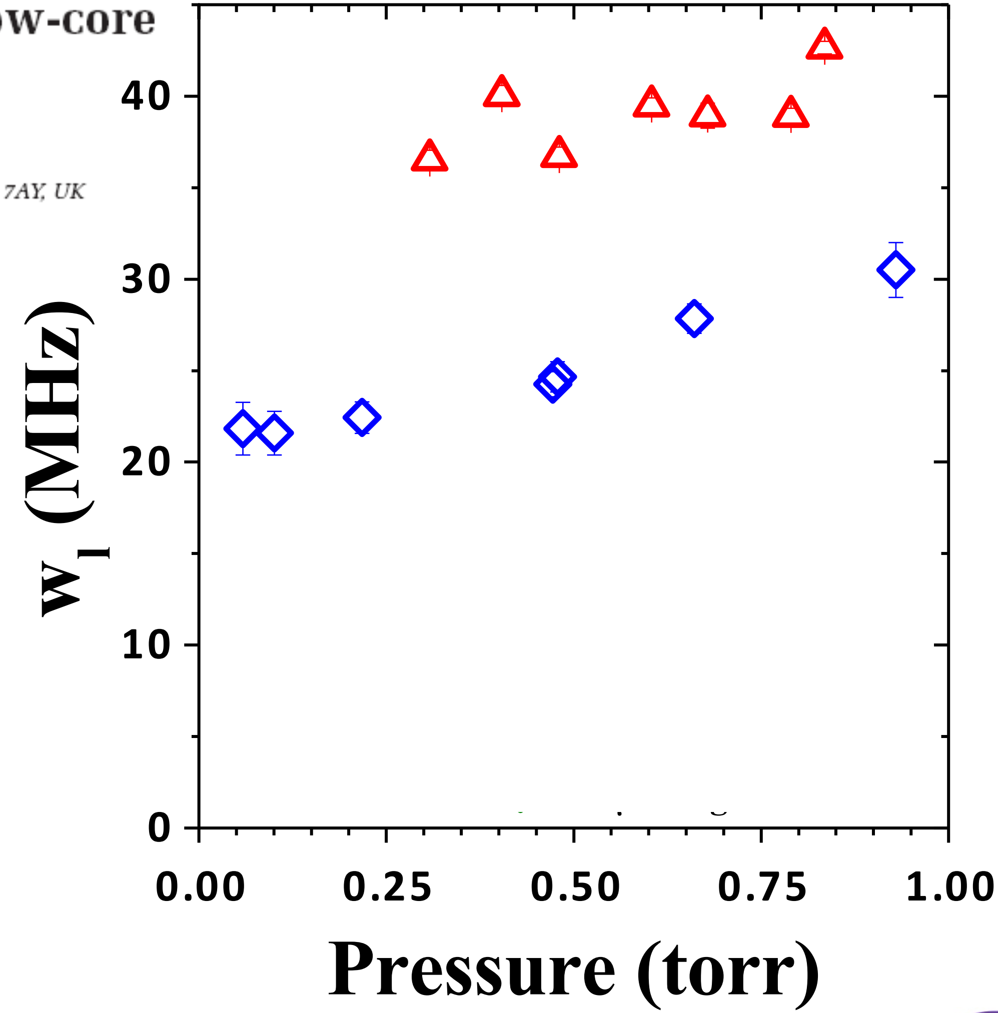
Large-pitch kagome-structured hollow-core photonic crystal fiber

F. Couny, F. Benabid, and P. S. Light
Centre for Photonics and Photonic Materials, University of Bath, Bath BA2 7AY, UK

48 x 68 μm

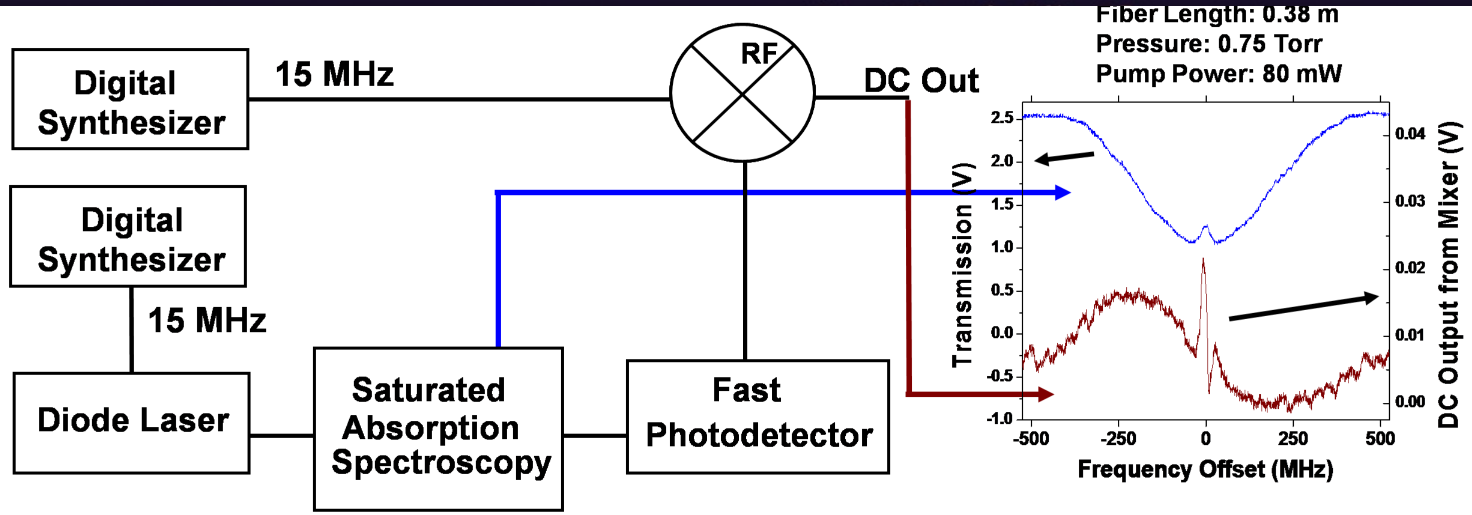




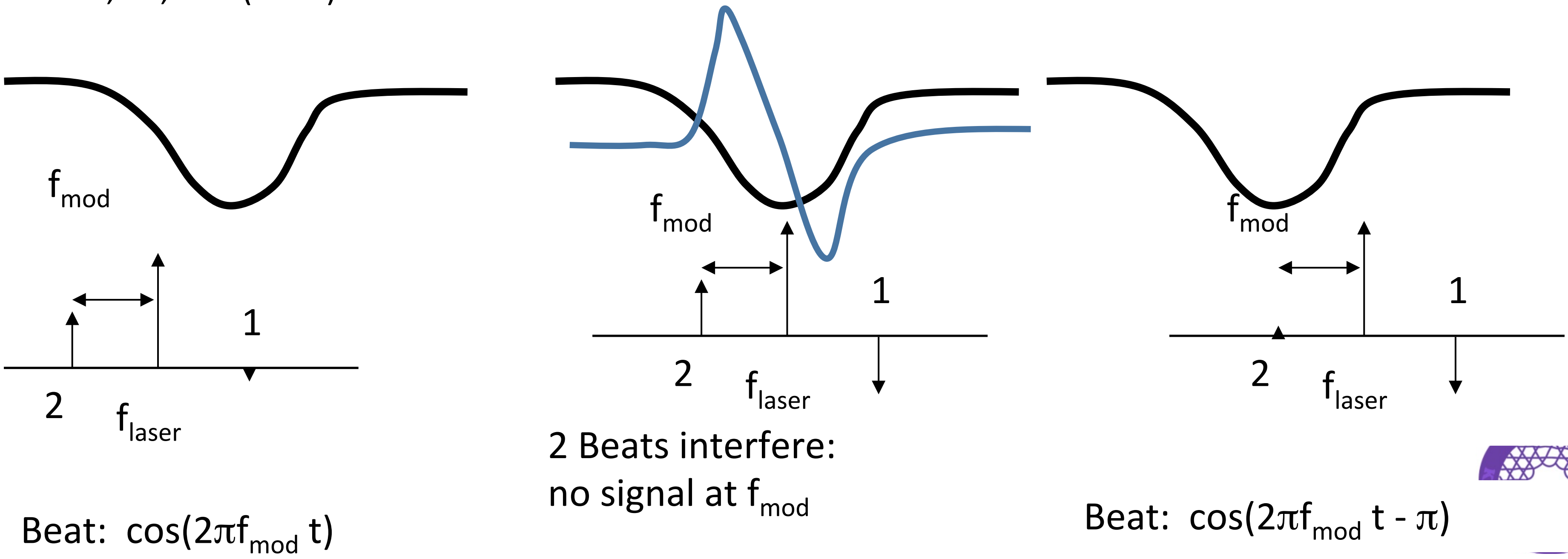


Transit Time Broadening!

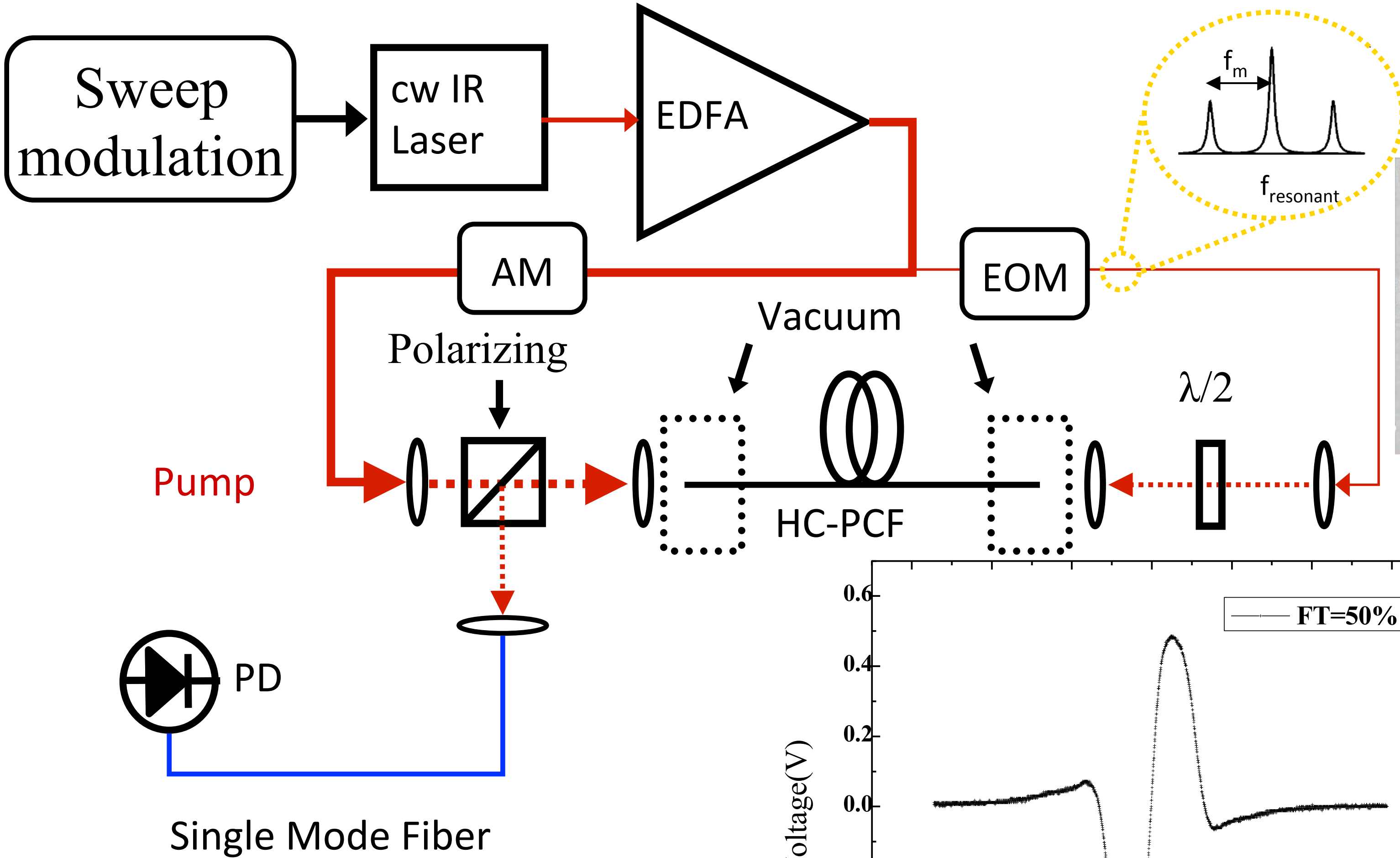
Using RF locking techniques to stabilize laser

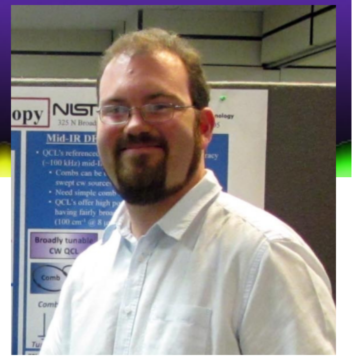


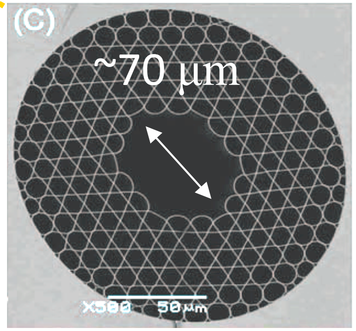
J. L. Hall, L. Hollberg, T. Baer, and H. G. Robinson, "Optical heterodyne saturation spectroscopy," Appl. Phys. Lett., 39, 680 (1981).

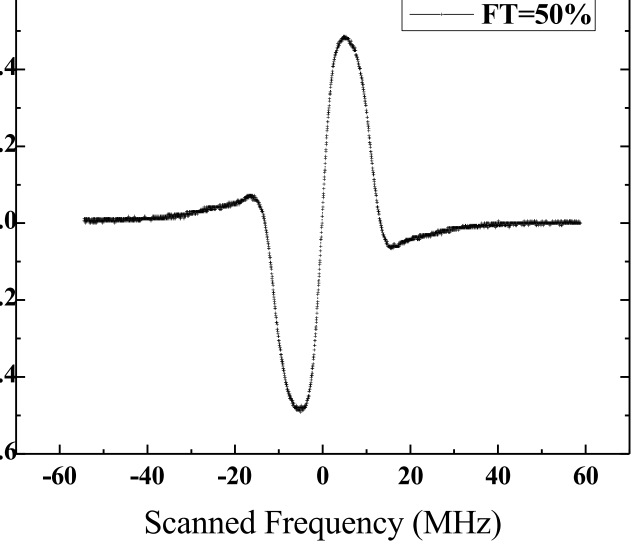


Laser Locked to Sub-Doppler Feature



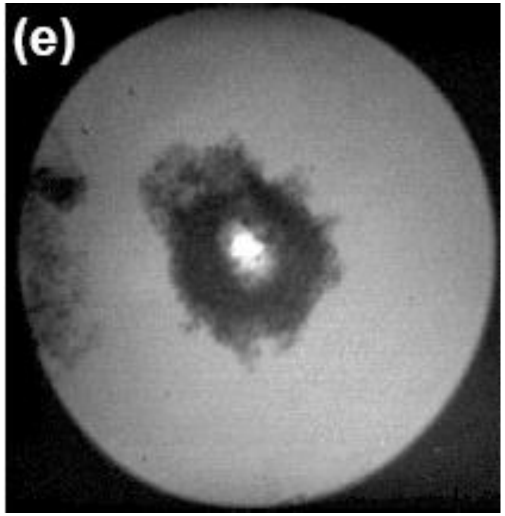


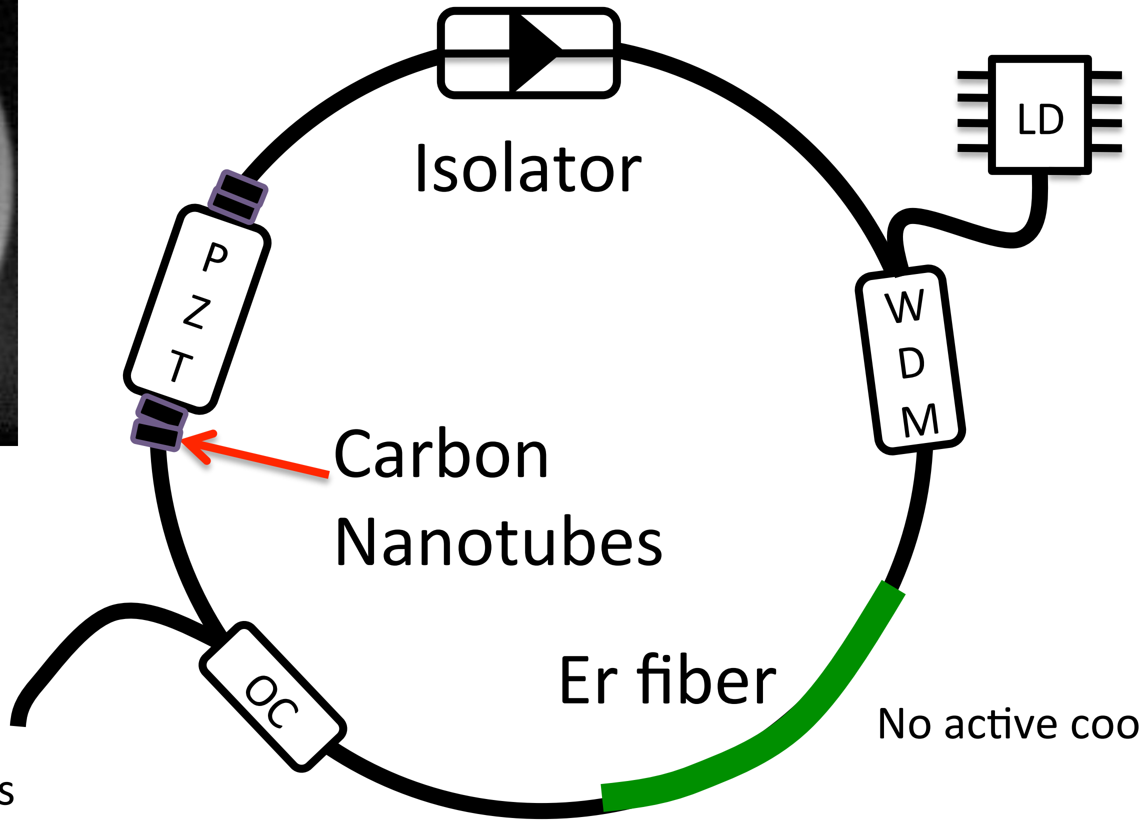




Drever, Hall, et. al. Appl. Opt. B (1983).

167 MHz repetition frequency carbon nanotube fiber laser (CNFL)





Leading Optical Innovations

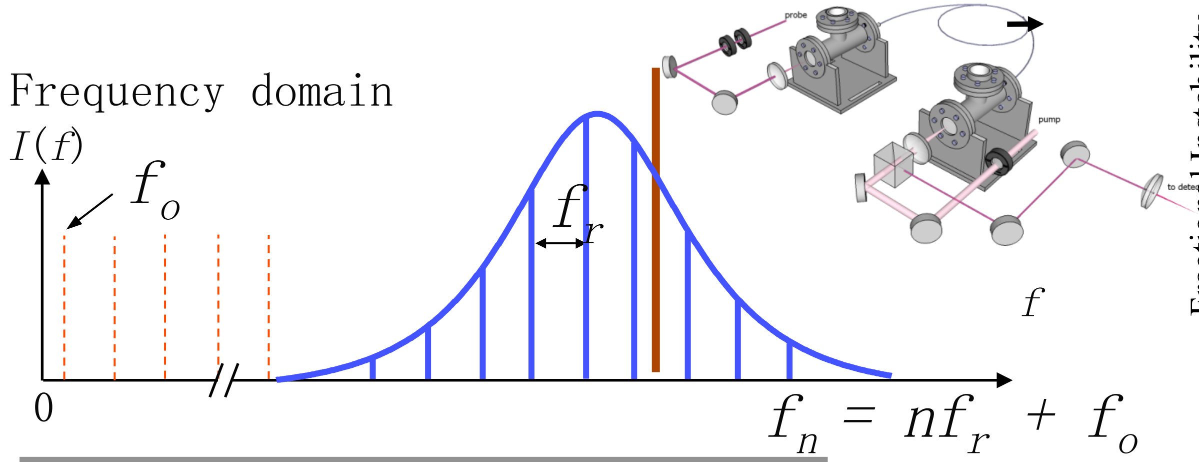
No active cooling!!!

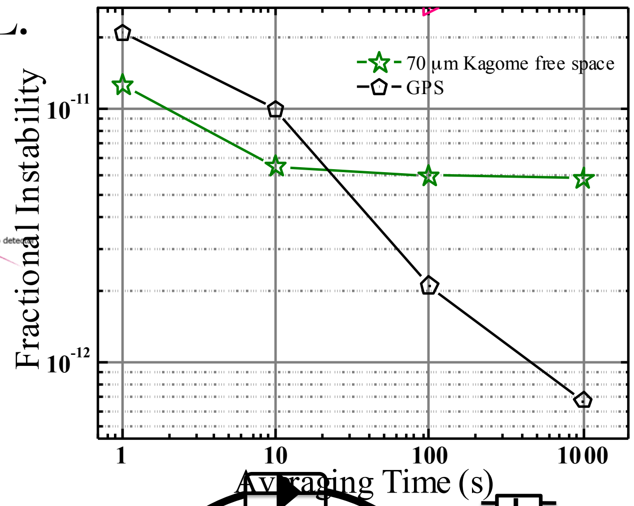
~ 1 mW and 250 fs

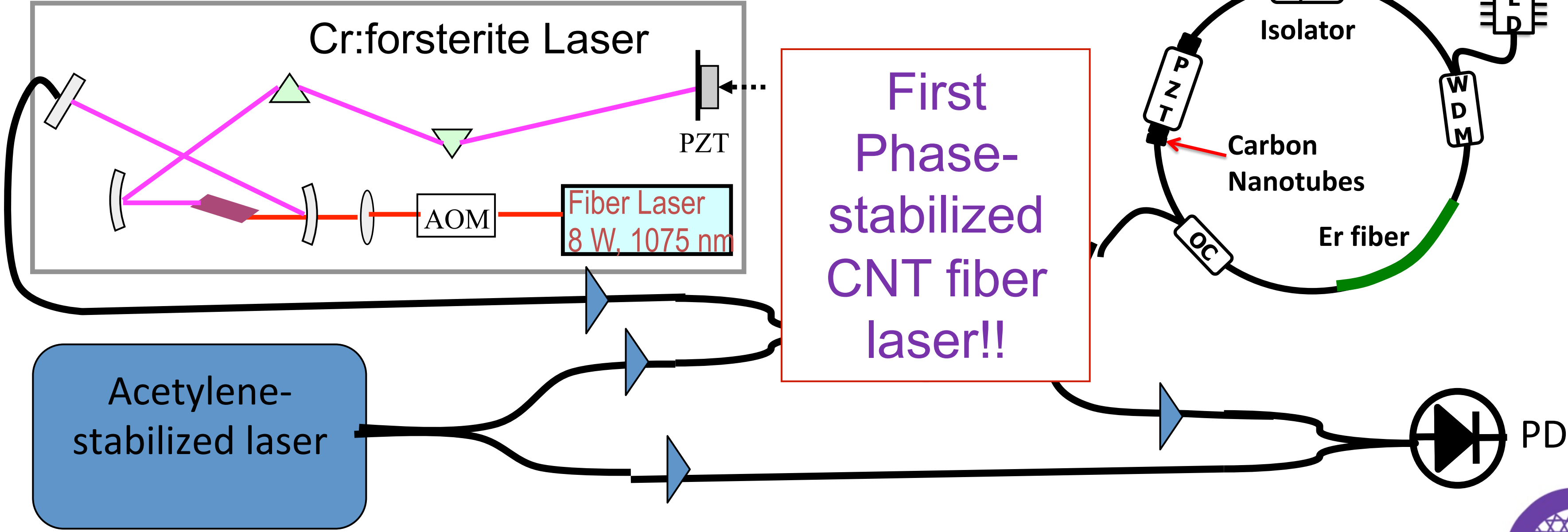
- *J. W. Nicholson et al. "Optically driven deposition of single-walled carbon-nanotube saturable absorbers on optical fiber end-face," Opt. Express 15, 9176-9183 (2007)*
- *J. W. Nicholson and D. J. DiGiovanni, "High repetition frequency, low noise, fiber ring lasers modelocked with carbon nanotubes," IEEE Photon. Technol. Lett. 20, 2123-2125 (2008).*

Frequency Combs: Cr:forsterite and Carbon Nanotube

- Rb/GPS stability transferred to both Cr:f and CNFL.

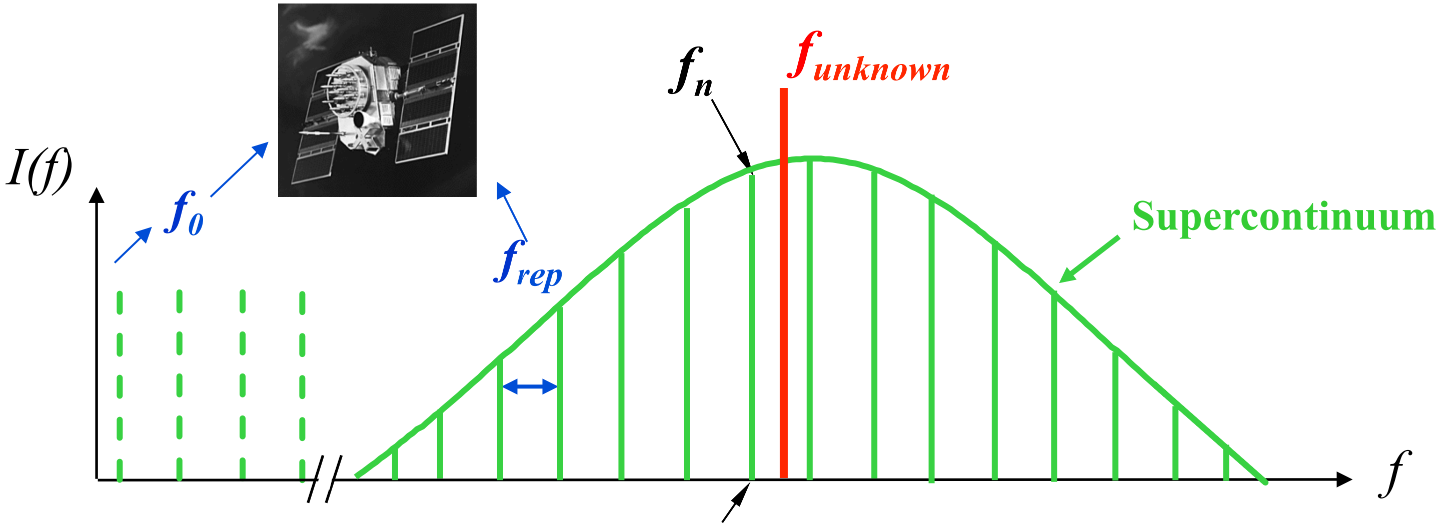






J. K. Lim *et al.*, Opt. Express 17, 14115-14120 (2009).
Karl A. Tillman *et al.*, Appl. Opt. 48, 6980-6989 (2009).

Absolute frequency measurements



$$f_n = nf_{rep} + f_0$$

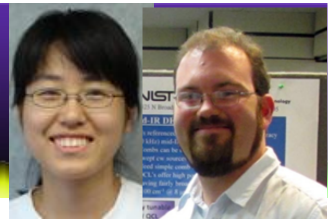
$$f_{unknown} = \pm f_n \mp f_{beat} = \pm nf_{rep} \pm f_0 \mp f_{beat}$$

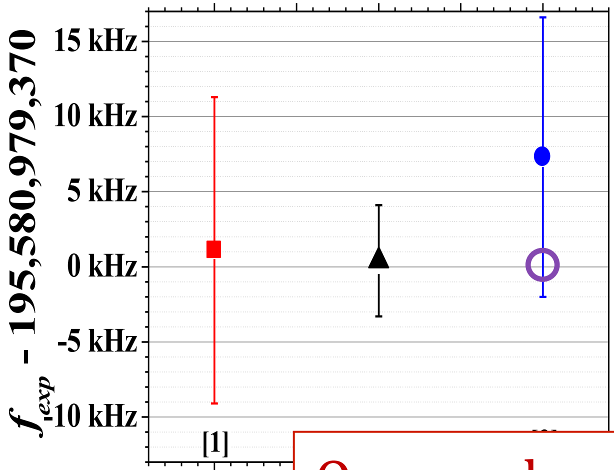
Example:

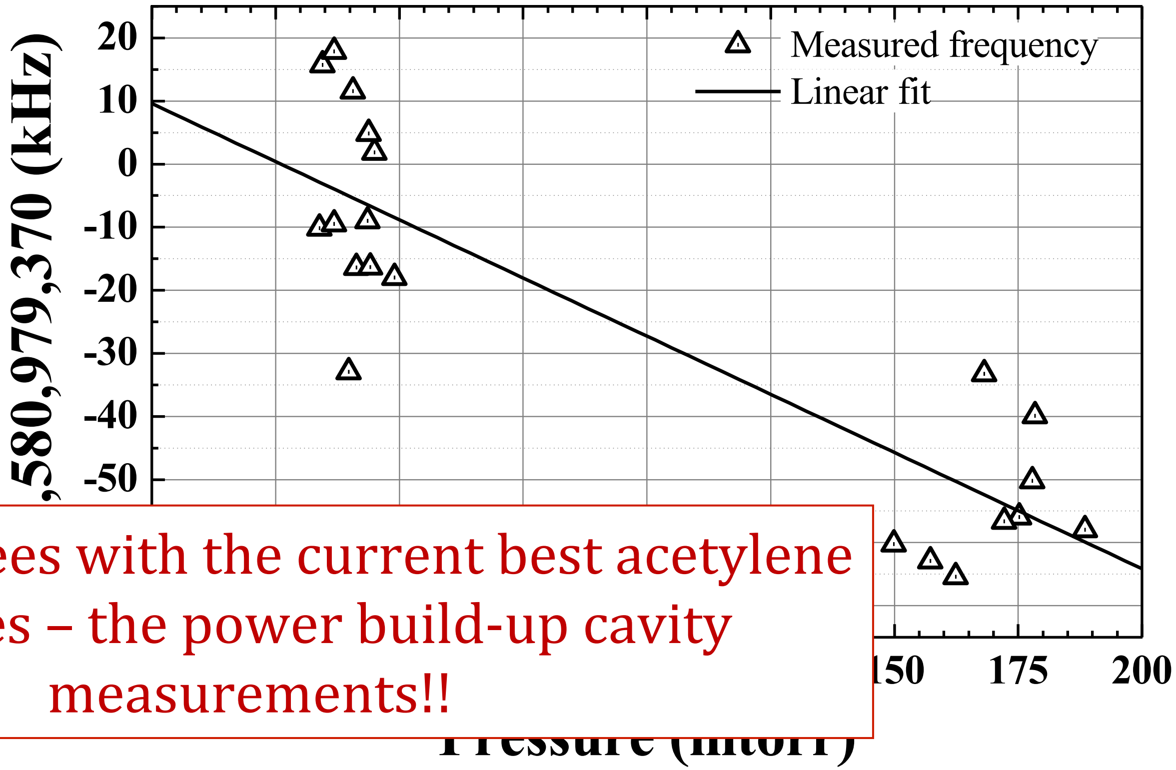
- $\uparrow f_{rep}$ ➡ if $f_{beat} \uparrow$ ➡ opp. sign for f_{rep} and f_{beat}
- $\uparrow f_0$ ➡ if $f_{beat} \downarrow$ ➡ same. sign for f_0 and f_{beat}

$$f_{unknown} = nf_{rep} - f_0 - f_{beat}$$

Absolute frequency of gas-filled kagome reference







Our work agrees with the current best acetylene references – the power build-up cavity measurements!!

[1] C. S. Edwards, et.al., Journal of Mol. Spec. **234**, 143-148 (**2005**).

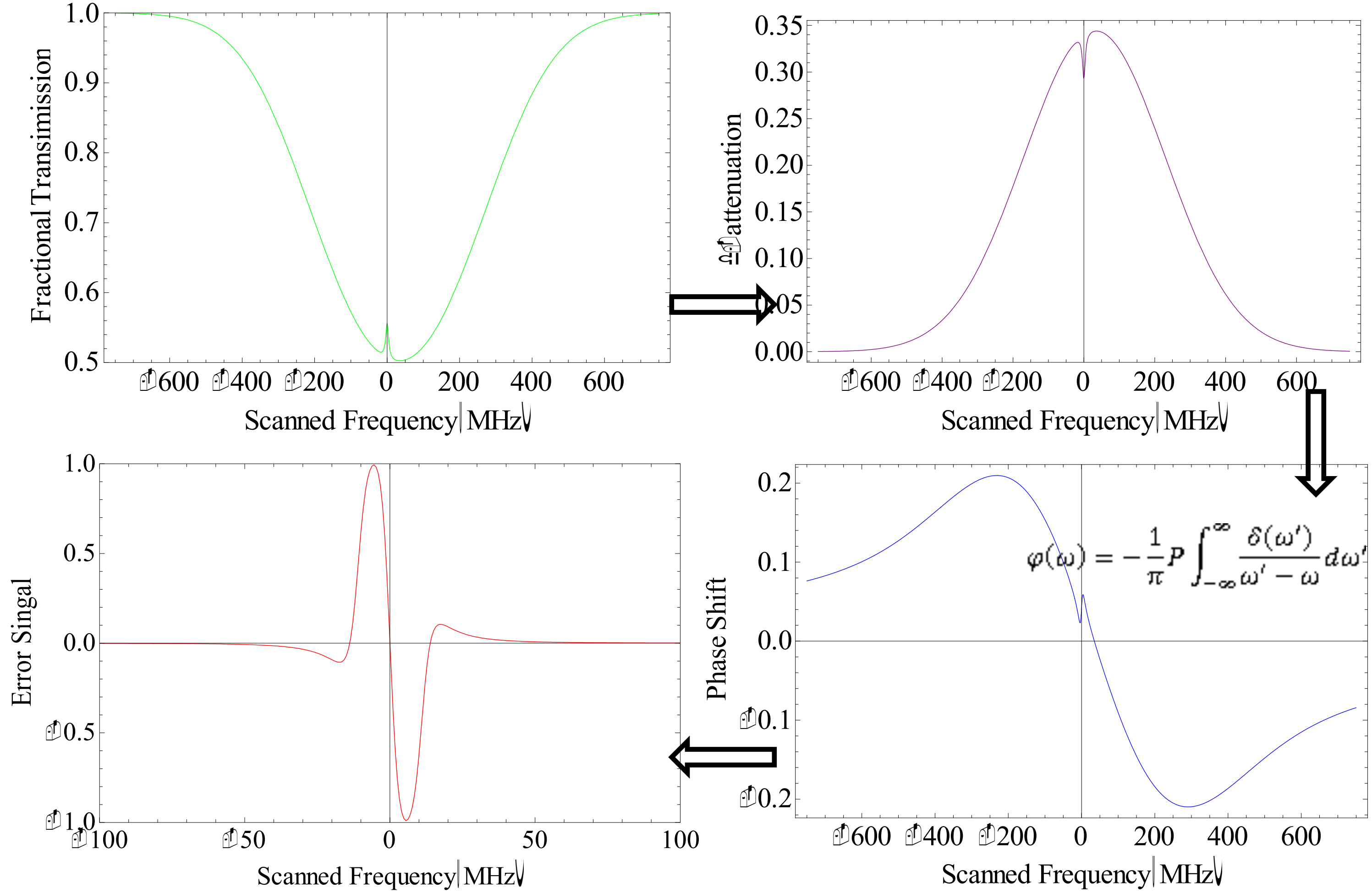
[2] A. A. Madej, et.al., JOSAB **23**, 2200-2208 (**2006**).

[3] **Our work:** K. Knabe, et.al., Opt. Express **17**(18), 16017 - 16026 (2009).

Modification: C. Wang, et.al. Appl. Opt. **52**, 5430-5439 (**2013**).

FM MODELING: DISPERSIVE ERROR SIGNAL CALCULATION

The Pound-Drever-Hall (PDH) locking technique used in the SAS depends on the complete information of the amplitude and phase shift on the carrier and two modulated sidebands (± 22 MHz).

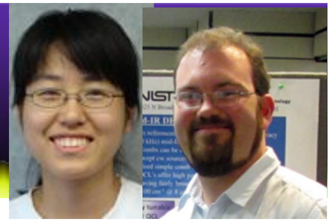


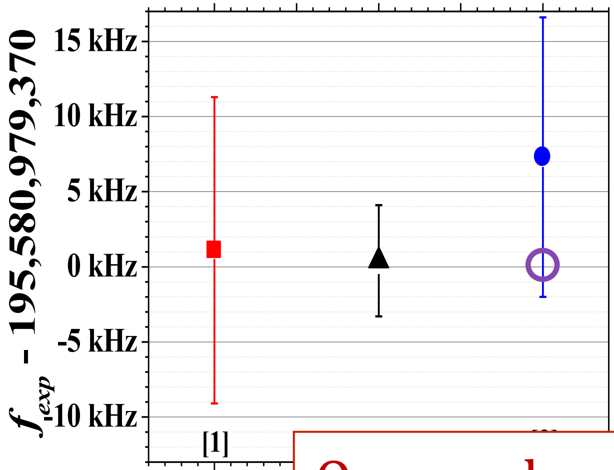
Amplitude:
theoretical & experimental saturated absorption feature

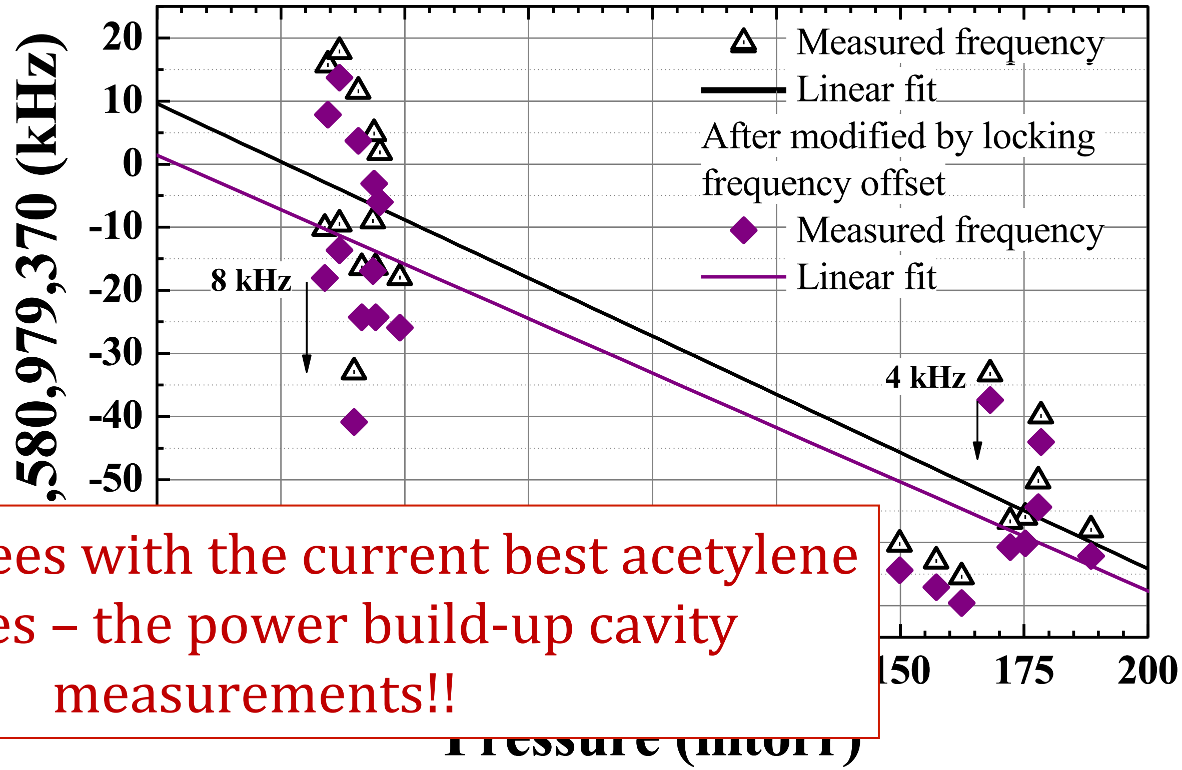
Phase shift:
Kramer-Kronig relation of amplitude (attenuation coefficient)

Bjorklund et. al. Appl. Phys. B 32, 145-152 (1983)

Absolute frequency of gas-filled kagome reference







Our work agrees with the current best acetylene references – the power build-up cavity measurements!!

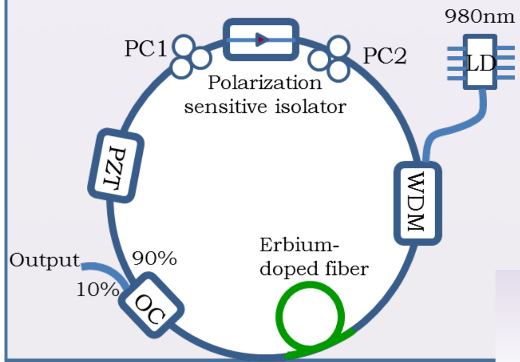
[1] C. S. Edwards, et.al., Journal of Mol. Spec. **234**, 143-148 (**2005**).

[2] A. A. Madej, et.al., JOSAB **23**, 2200–2208 (**2006**).

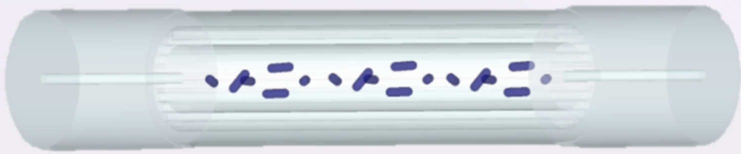
[3] Our work: K. Knabe, et.al., Opt. Express **17**(18), 16017 - 16026 (**2009**).

Modification: C. Wang, et.al. Appl. Opt. **52**, 5430-5439 (**2013**).

Goal: all-fiber comb and all-fiber reference

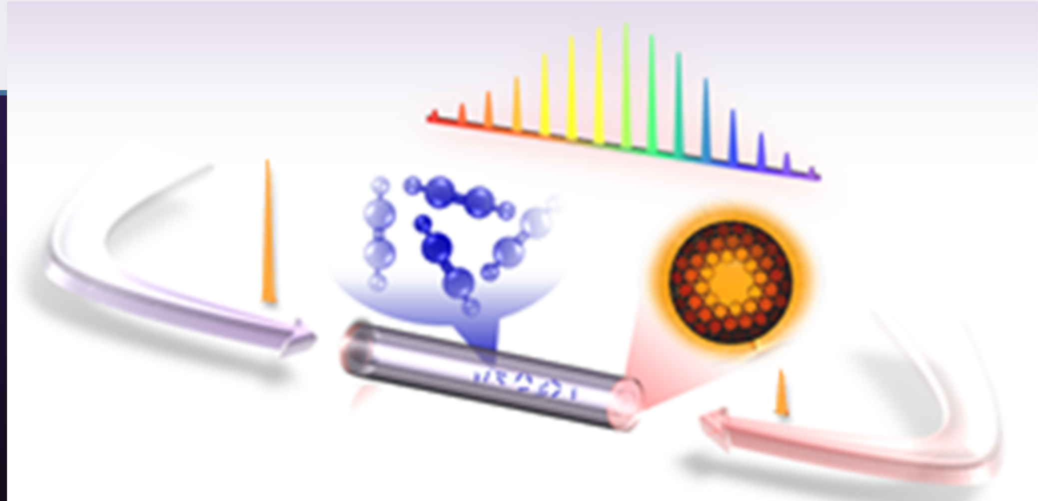


fs Er-doped fiber laser +



gas-filled fiber

=



Optically referenced portable frequency comb system

(no ultrastable RF required)

Direct comb stabilization to gas-filled fiber reference

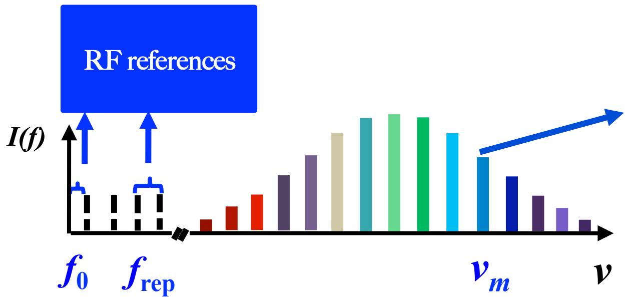
Motivation

Stabilization of single tooth to C_2H_2 transition

- **Single tooth amplification from nW to 10's of mW**
- **Saturated Absorption Spectroscopy**
- **Stability analysis**

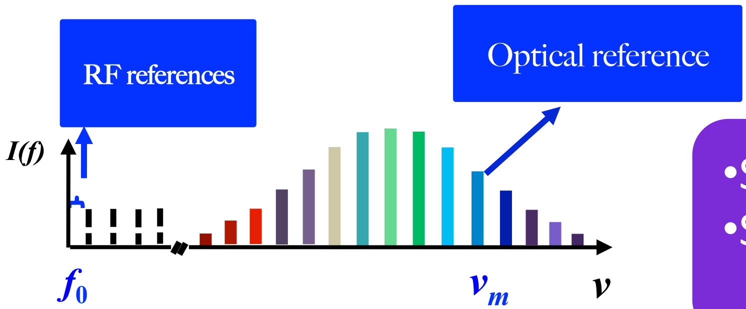
Advantages of optical referencing

- Stabilization of frequency combs
  - RF referenced combs



$$\sigma_{\nu_m} = \frac{\delta\nu_m}{\nu_m} = \frac{m\times\delta f_{rep}+\delta f_0}{\nu_m} = m\times\frac{\delta f_{rep}}{\nu_m}+\frac{\delta f_0}{\nu_m}$$

  - Optically referenced combs

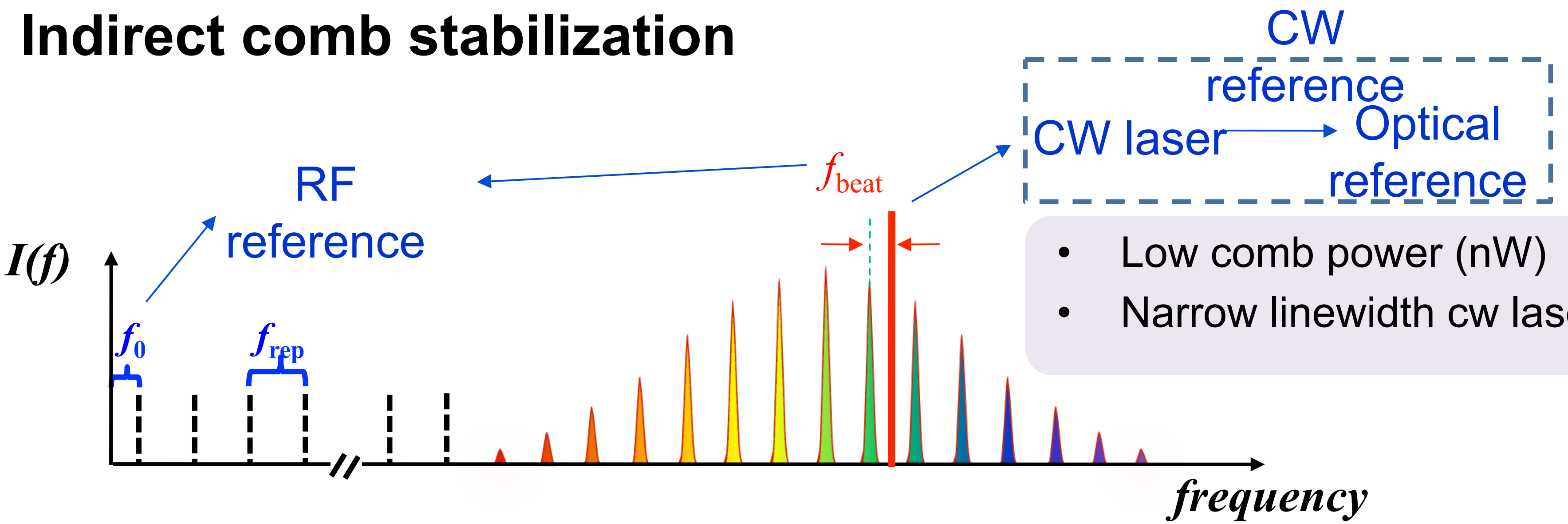


Advantages:

- Short term stability across optical spectrum
- Stable RF read out at f_{rep}

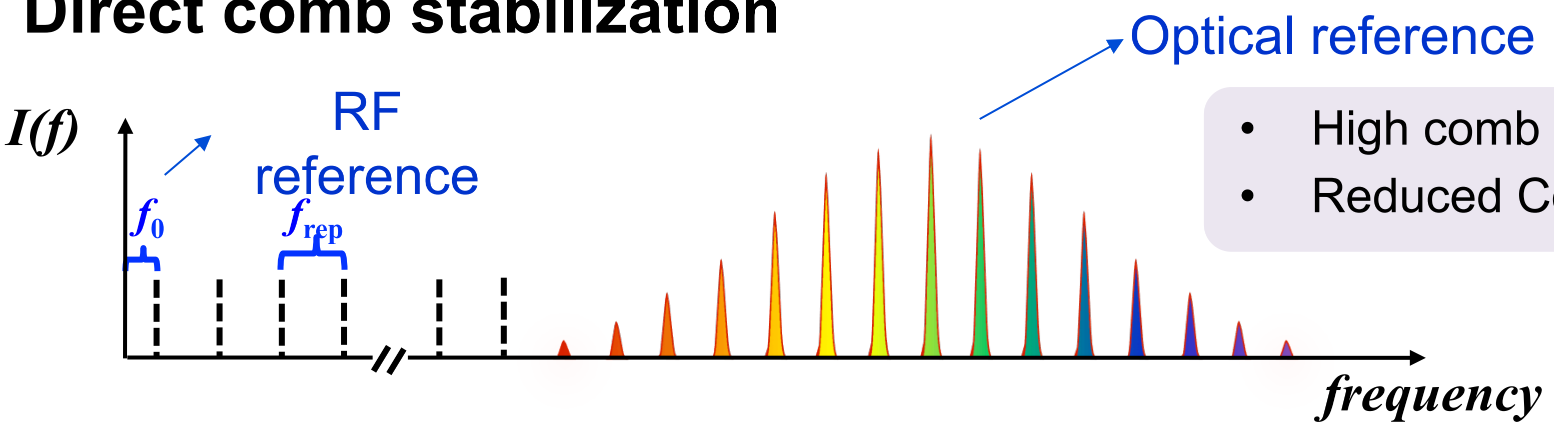
Indirect vs. Direct comb stabilization

Indirect comb stabilization



- Low comb power (nW)
- Narrow linewidth cw laser

Direct comb stabilization



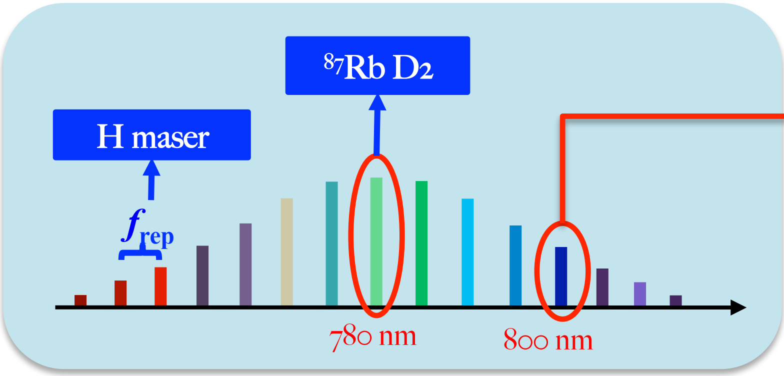
- High comb power (mW)
- Reduced Complexity

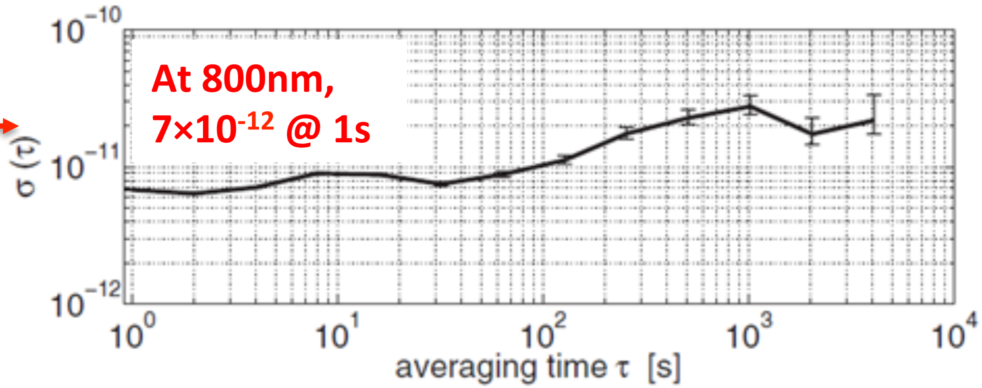
Ti:Sapph direct stabilization single-tooth sub-Doppler spectroscopy

PHYSICAL REVIEW A **80**, 053806 (2009)

Optical frequency stabilization of a 10 GHz Ti:sapphire frequency comb by saturated absorption spectroscopy in ^{87}rubidium

D. C. Heinecke,[1,2,*] A. Bartels,[2,3] T. M. Fortier,[1] D. A. Braje,[1] L. Hollberg,[4] and S. A. Diddams[1,†]
[1]*National Institute of Standards and Technology, 325 Broadway M.S. 847, Boulder, Colorado 80305, USA*
[2]*Center for Applied Photonics, University of Konstanz, Universitätsstrasse 10, 78457 Konstanz, Germany*
[3]*Gigaoptics GmbH, Blarerstrasse 56, 78462 Konstanz, Germany*





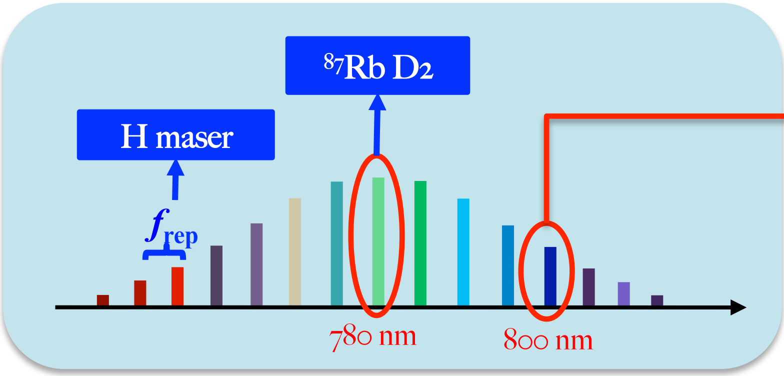
- 10 GHz rep rate, mW/tooth directly from Ti:S oscillator (no amplification)
- Rb saturates with few mW.

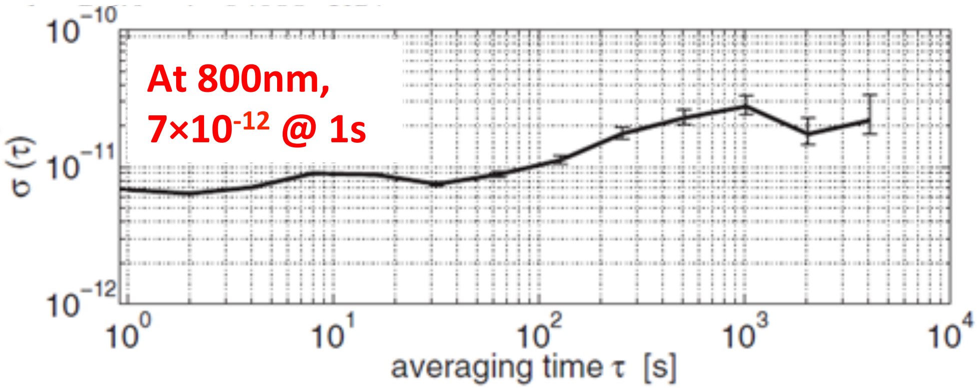
Related work

PHYSICAL REVIEW A **80**, 053806 (2009)

Optical frequency stabilization of a 10 GHz Ti:sapphire frequency comb by saturated absorption spectroscopy in ^{87}rubidium

D. C. Heinecke,[1,2,*] A. Bartels,[2,3] T. M. Fortier,[1] D. A. Braje,[1] L. Hollberg,[4] and S. A. Diddams[1,†]
[1]*National Institute of Standards and Technology, 325 Broadway M.S. 847, Boulder, Colorado 80305, USA*
[2]*Center for Applied Photonics, University of Konstanz, Universitätsstrasse 10, 78457 Konstanz, Germany*
[3]*Gigaoptics GmbH, Blarerstrasse 56, 78462 Konstanz, Germany*





Challenges for fiber combs:

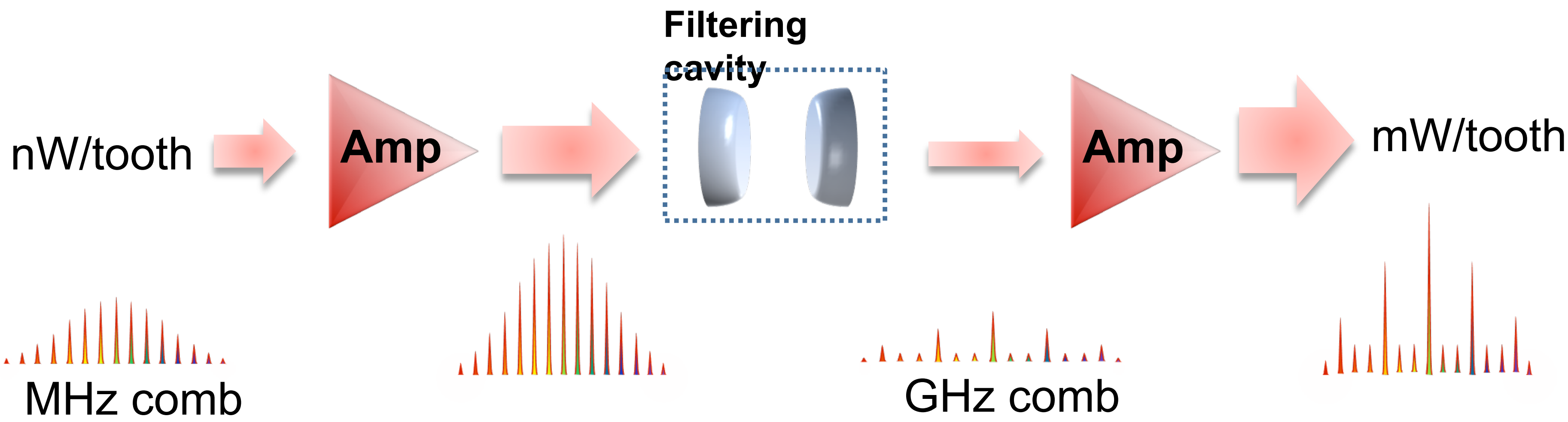
◆ **nW per tooth** (vs. **mW for NIST Ti:S**) for Direct Comb Spectroscopy

Requires power amplification by a factor of 10^6

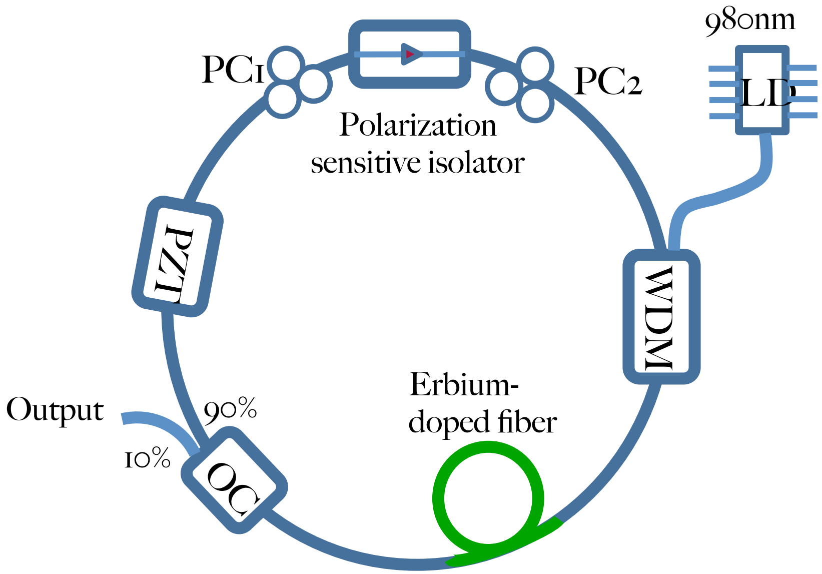
Challenge for comb amplification

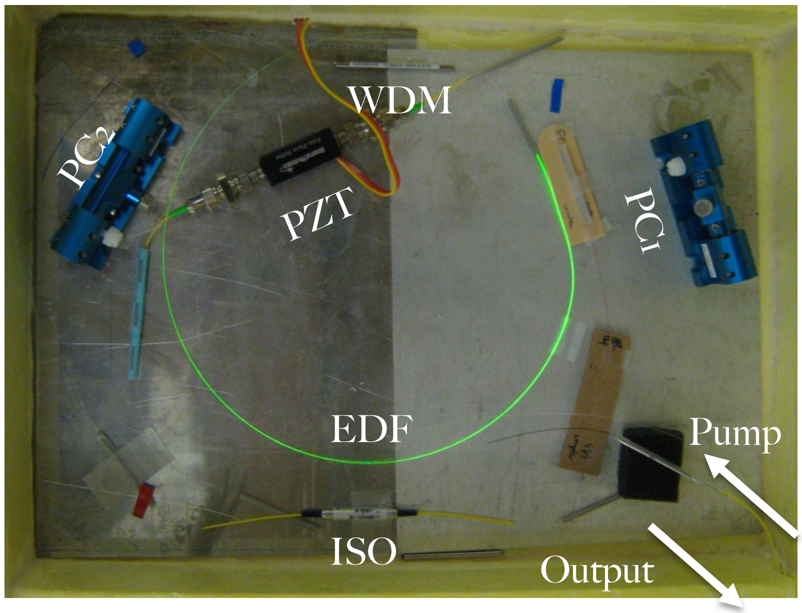
Amplifying MHz fiber comb

- Our solution:

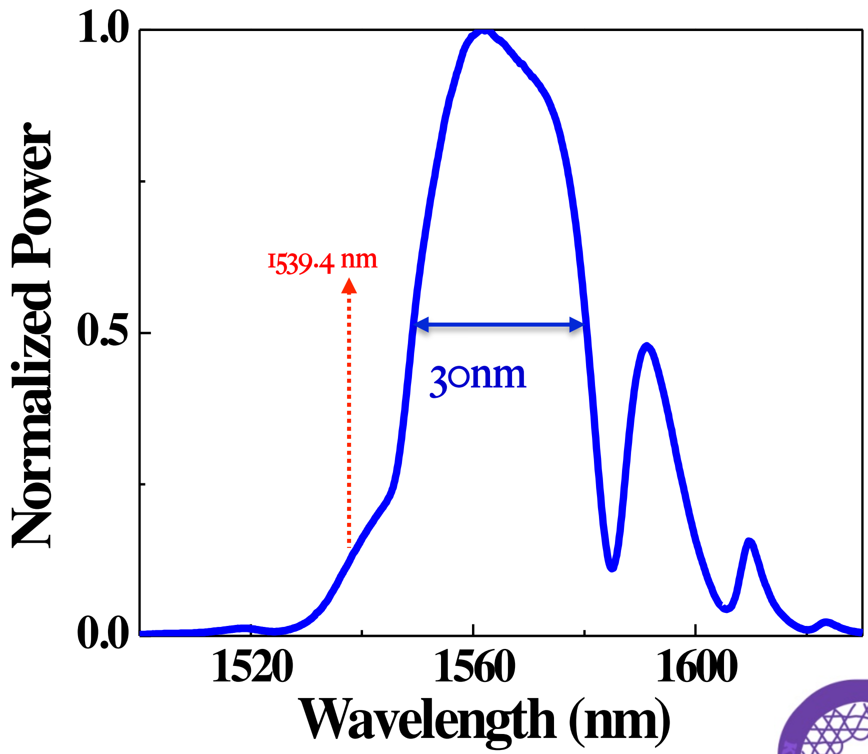


Modelocked Fiber Laser

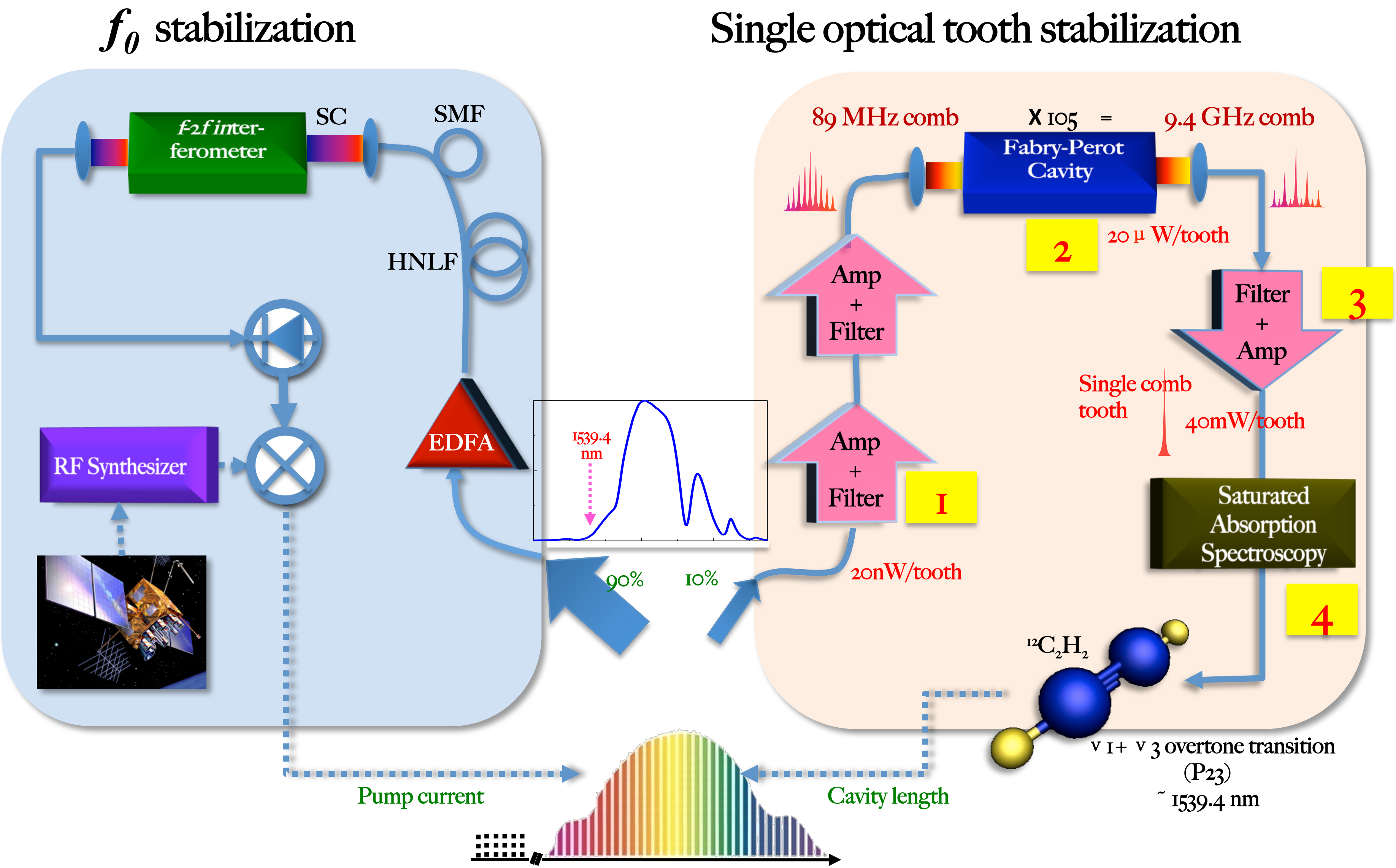




- EDF 110 as gain medium
- Pumped by 300 mW 980 nm LD
- Nonlinear Polarization Rotation
- f_{rep} = 89 MHz
- Output power ~ 4 mW

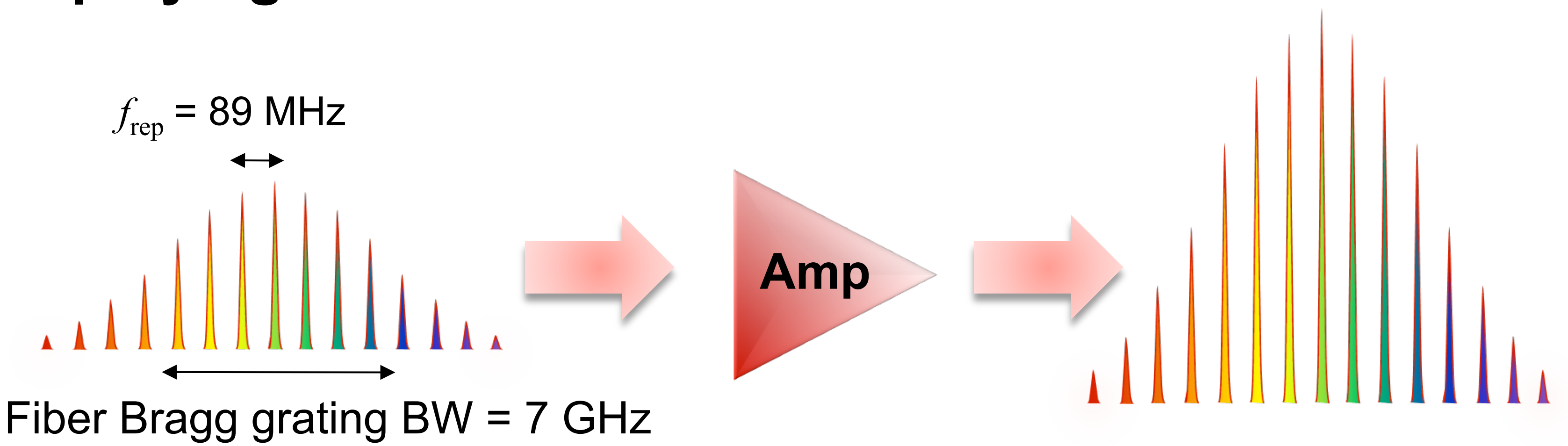


Comb Stabilization



Challenge for comb amplification

Amplifying MHz fiber comb



79 teeth × 40 mW/tooth = Requires **3 W average power !**

(P_{avg} = 1.5 μW)

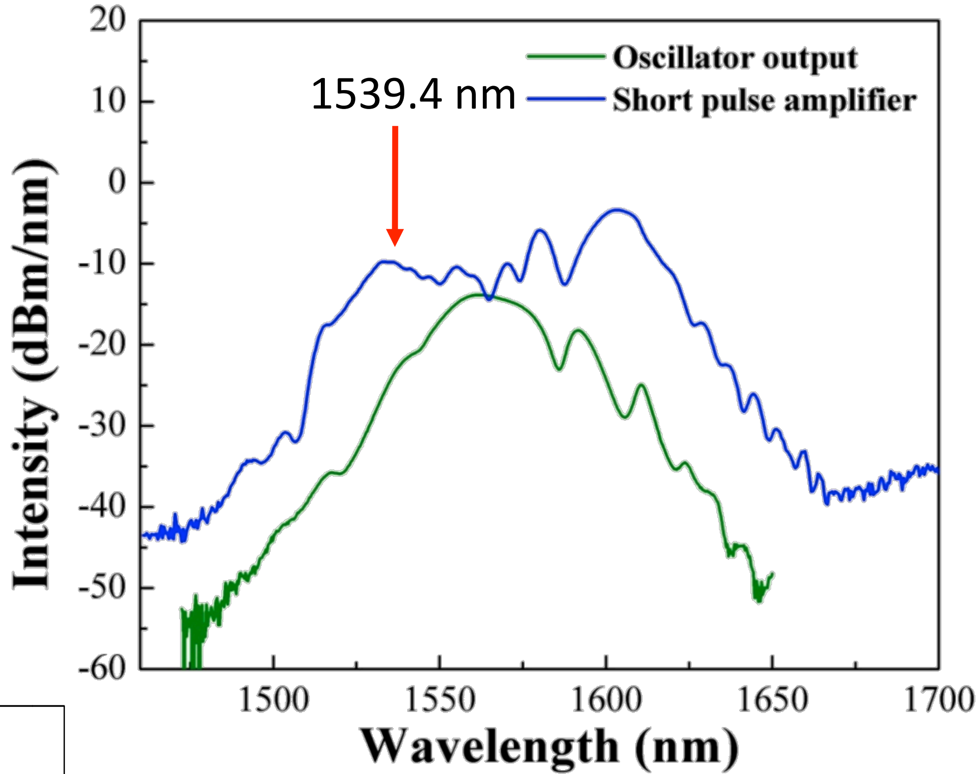
Single comb tooth saturation

- Significant amplification => degradation of comb SNR

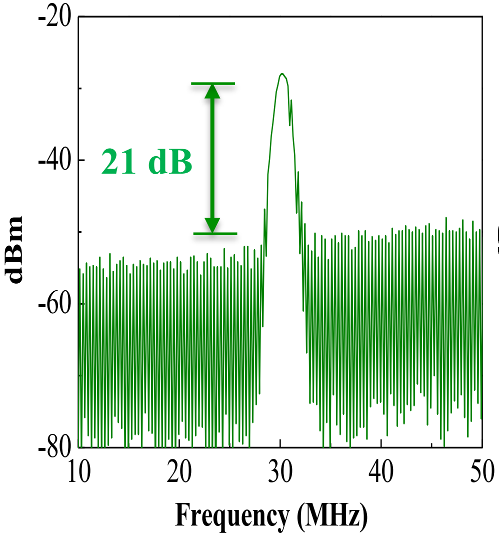
Home-made pre-amplifier

Short pulse fiber amplifier

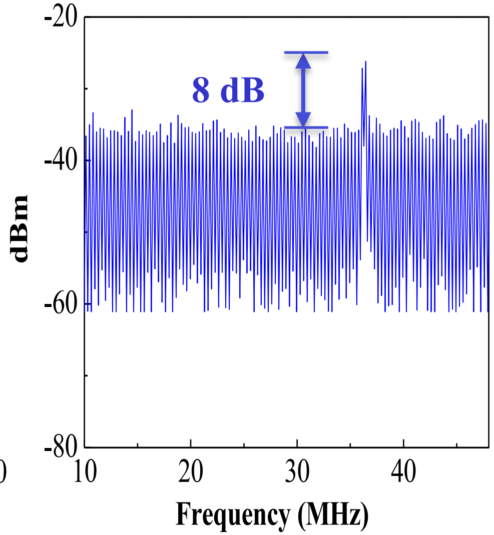
- Seeded by the oscillator comb
- EDF 110 as gain fiber
- Backward pumped by 1480 nm diode
- amplify and temporally compress pulses via solitonic effects



Oscillator /CW beat



Amp comb /CW beat

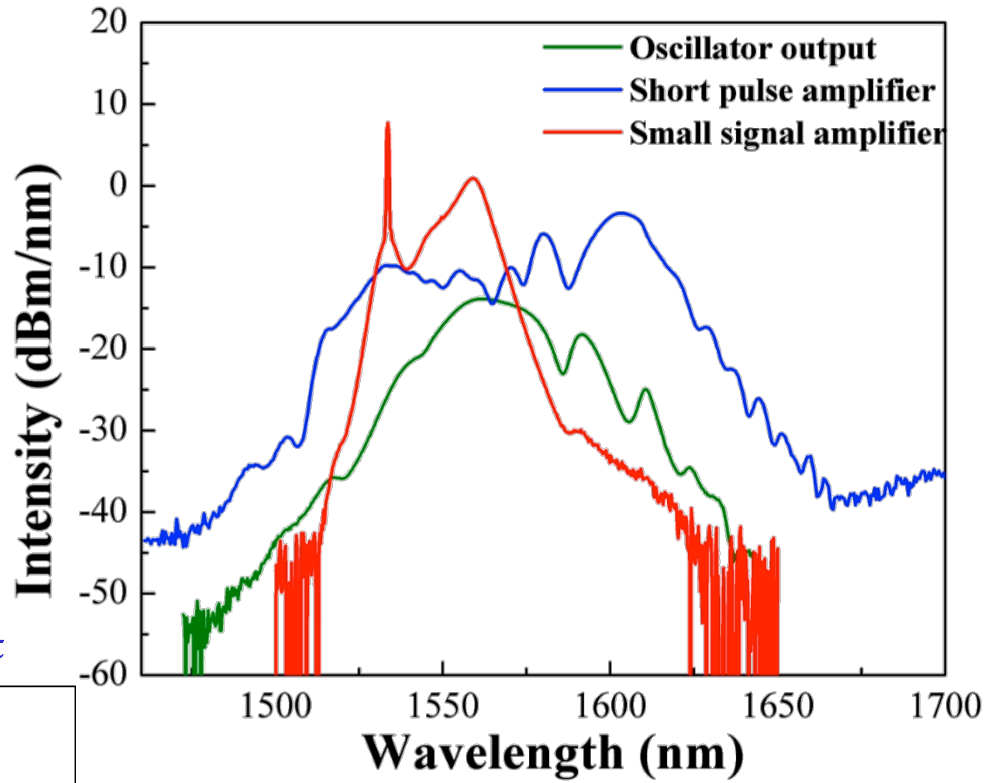


Degraded comb SNR

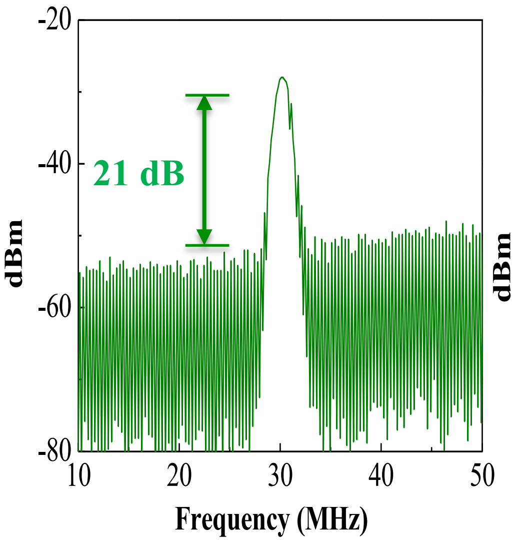
Home-made pre-amplifier

Small signal gain CW amplifier

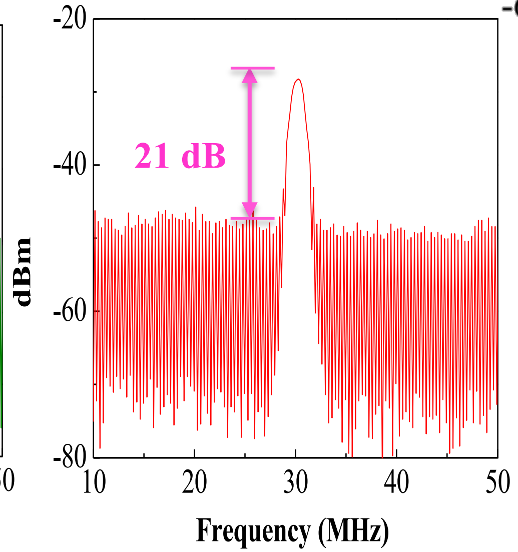
- EDF 80, 1 meter length
- Mainly forward pumped by 980 nm LD
- Seed in with 0.4 nm BW comb



Oscillator /CW beat



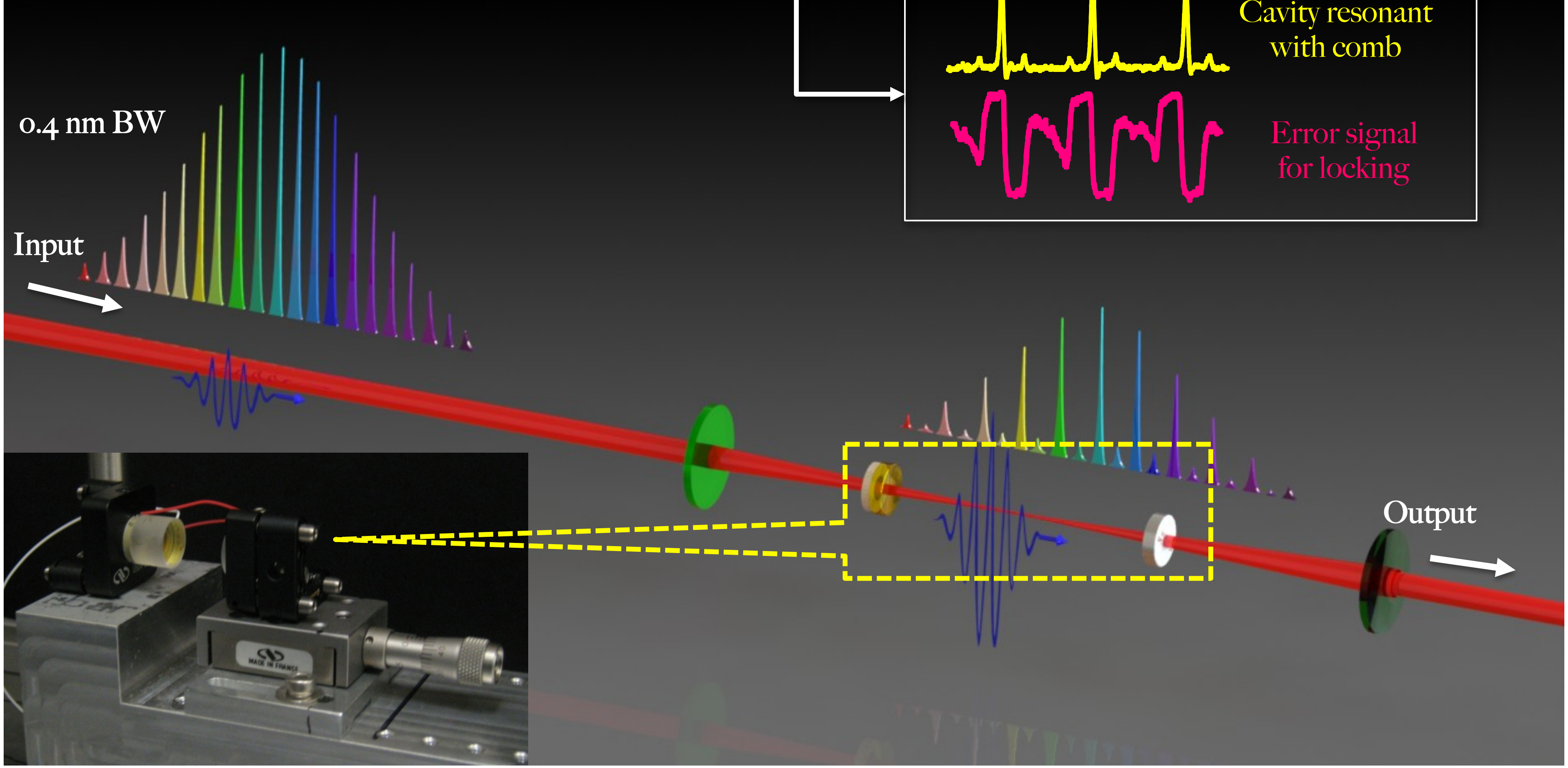
Amp comb /CW beat



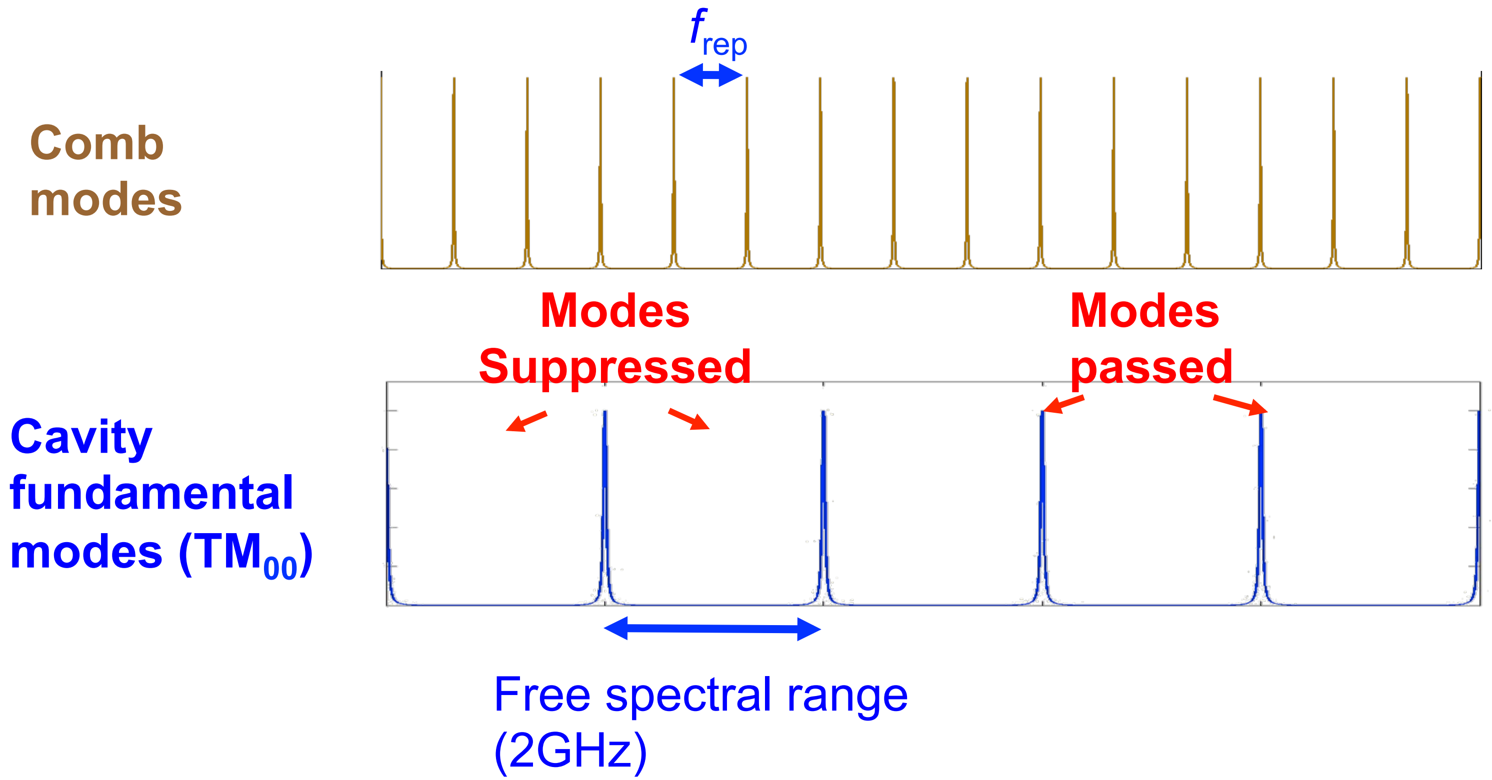
Preserved comb SNR

Fabry-Perot Filtering Cavity

- Free spectral range (FSR) ~ 9.4 GHz (105 : 1 selection ratio)
- Suppression ratio ~25 dB
- Pound-Drever-Hall Locking

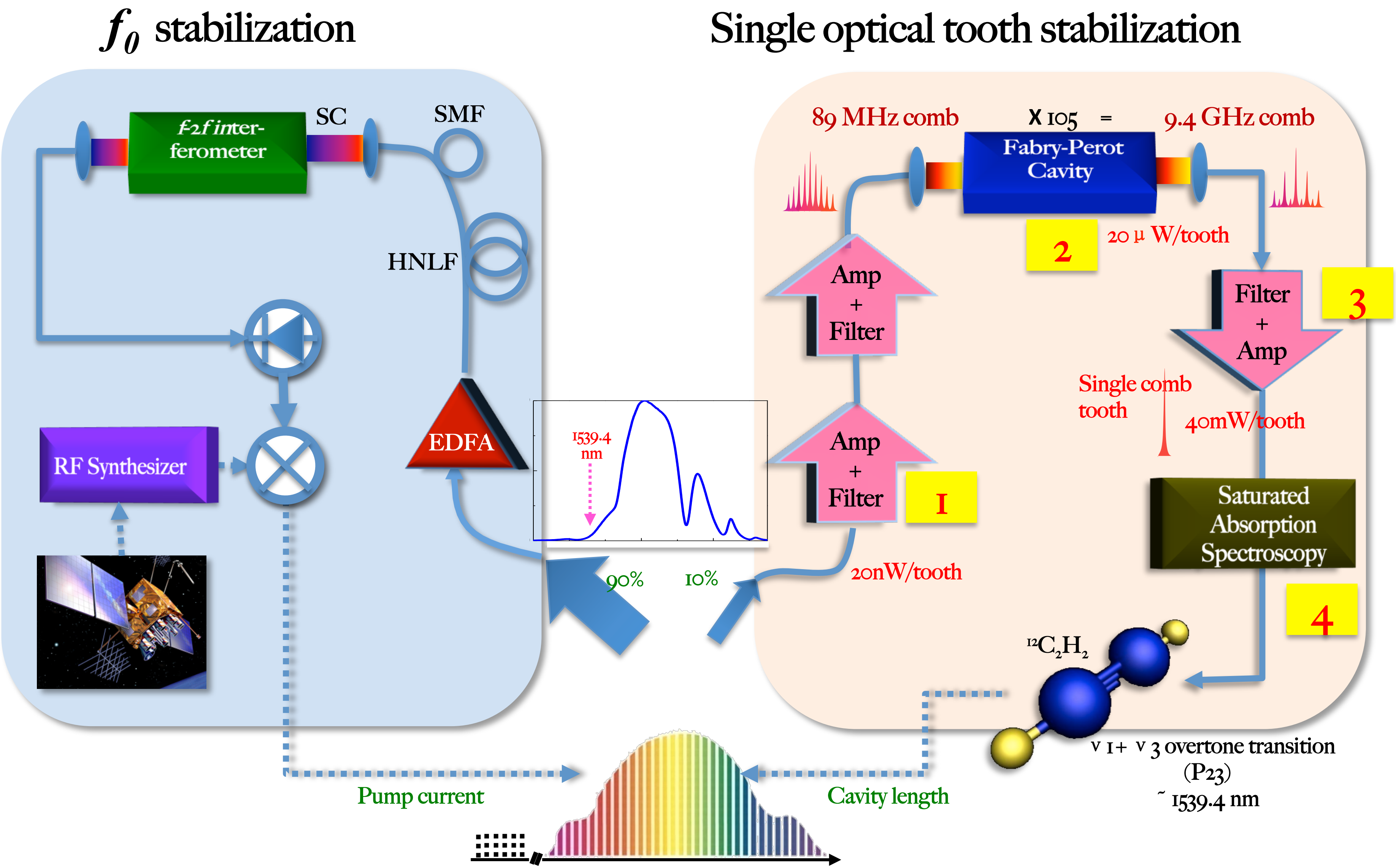


Filtering Cavity



- Mode suppression (cavity finesse)
- Cavity spatial mode filtering (ROC)
- Mode matching (beam size, wave front matching)
- Cavity stability

Comb Stabilization



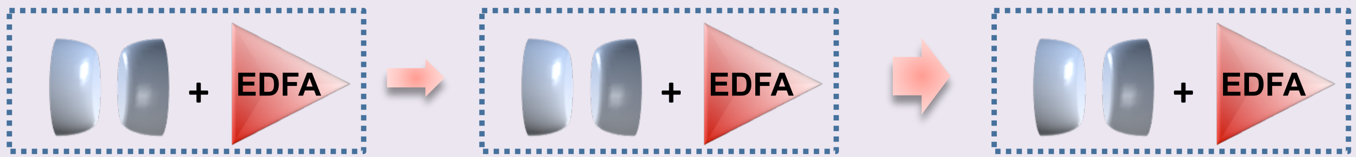
GHz comb amplification

Problem:

- Re-amplification of suppressed teeth
- Degradation of comb SNR

Large gain BW: 1520-1565 nm

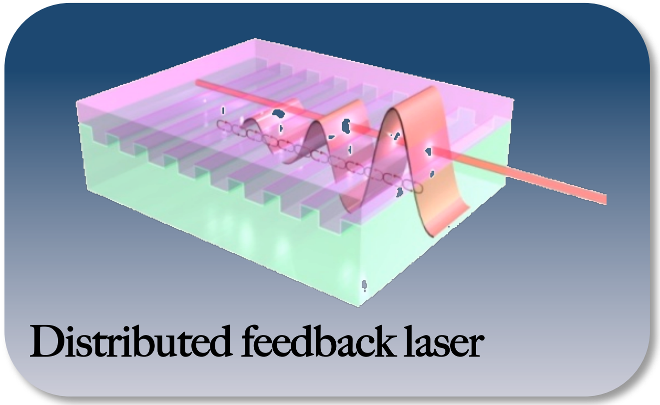
Astrocomb:



GHz comb amplification

H. Y. Ryu et. al., *Opt. Express*,16, 2867 (2008)

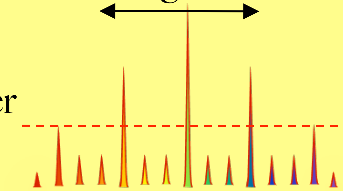
Our solution:
Injection locking technique



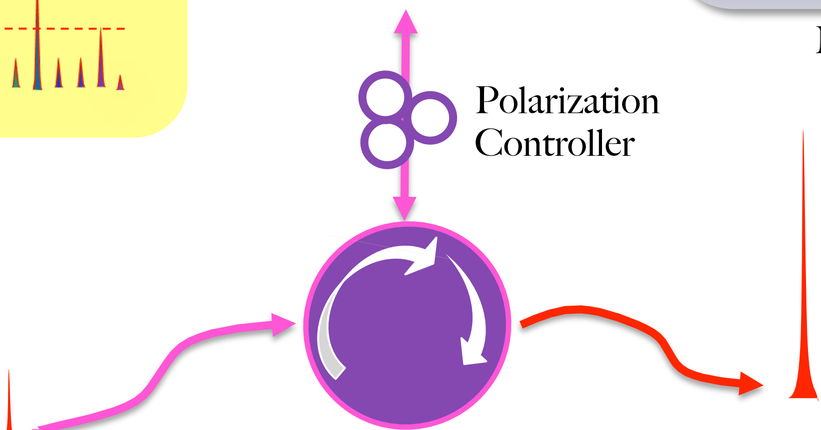
No built-in isolator

GHz gain BW

20 μ W power threshold



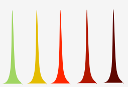
DFB



Single comb tooth
(9.2 GHz spacing)
(Our case: 50 μ W/tooth)

Single-tooth amplified
(Our case: 40 mW)

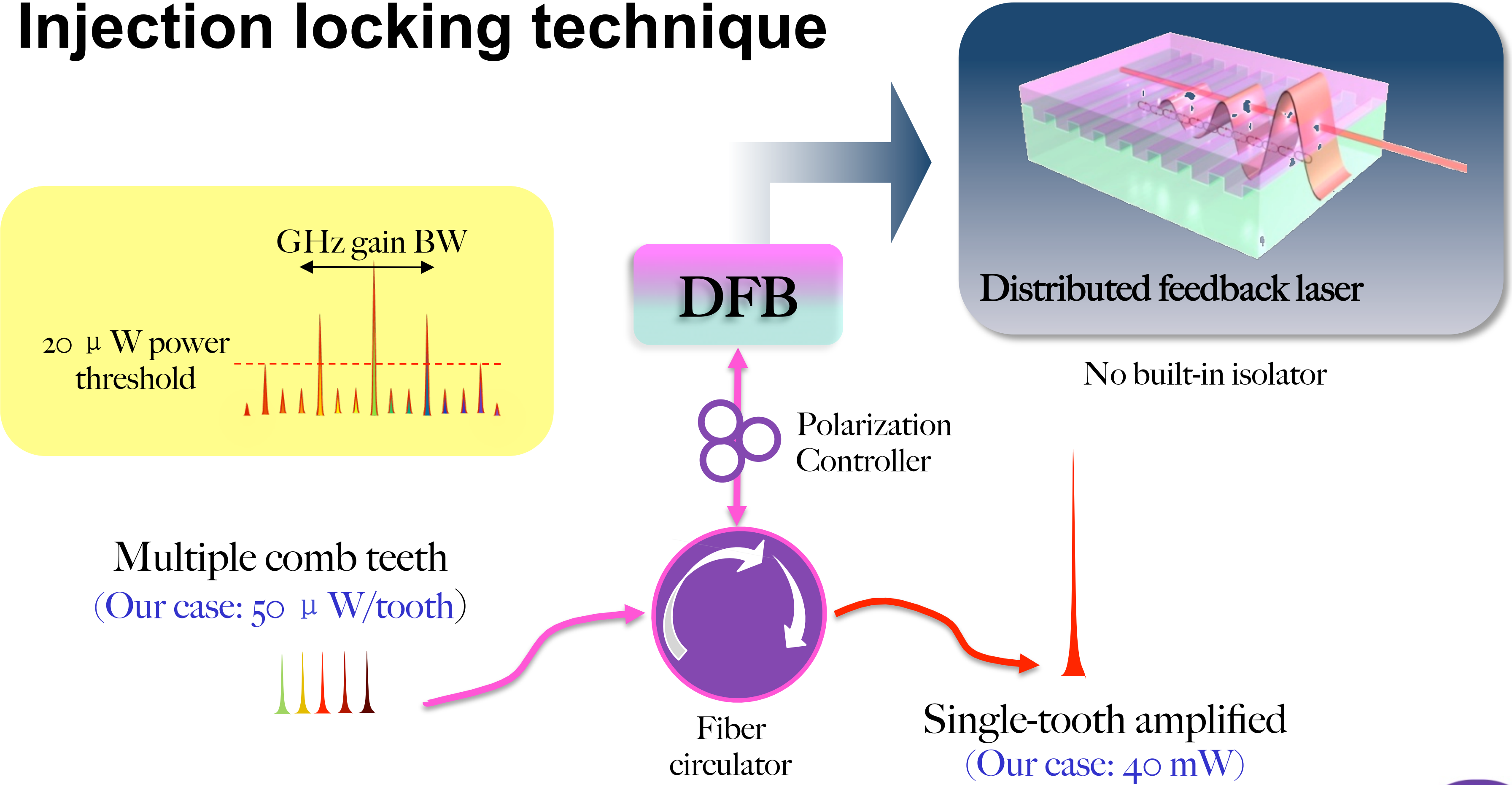
Multiple comb teeth
(~2 GHz spacing)
(Our case: 50 μ W/tooth)



Mode competition
unstable error signal
(Our case: 40 mW)

GHz comb amplification

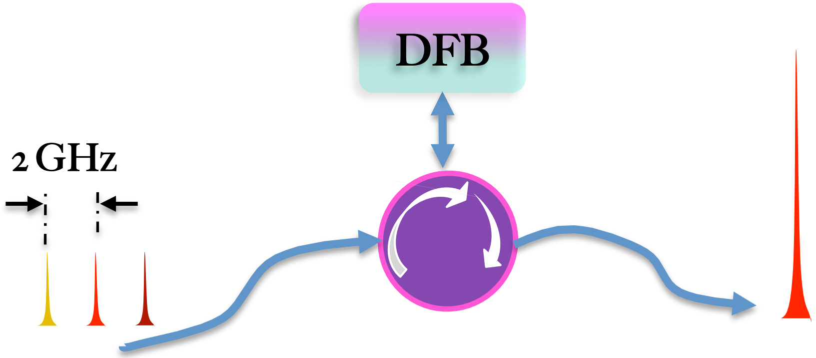
Our solution:
Injection locking technique

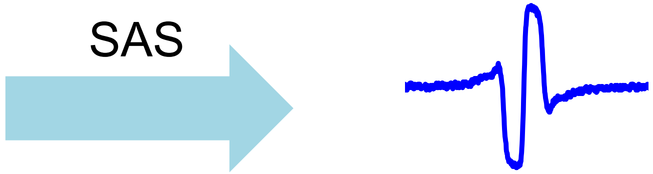


H. Y. Ryu et. al., *Opt. Express*,**16**, 2867 (2008)

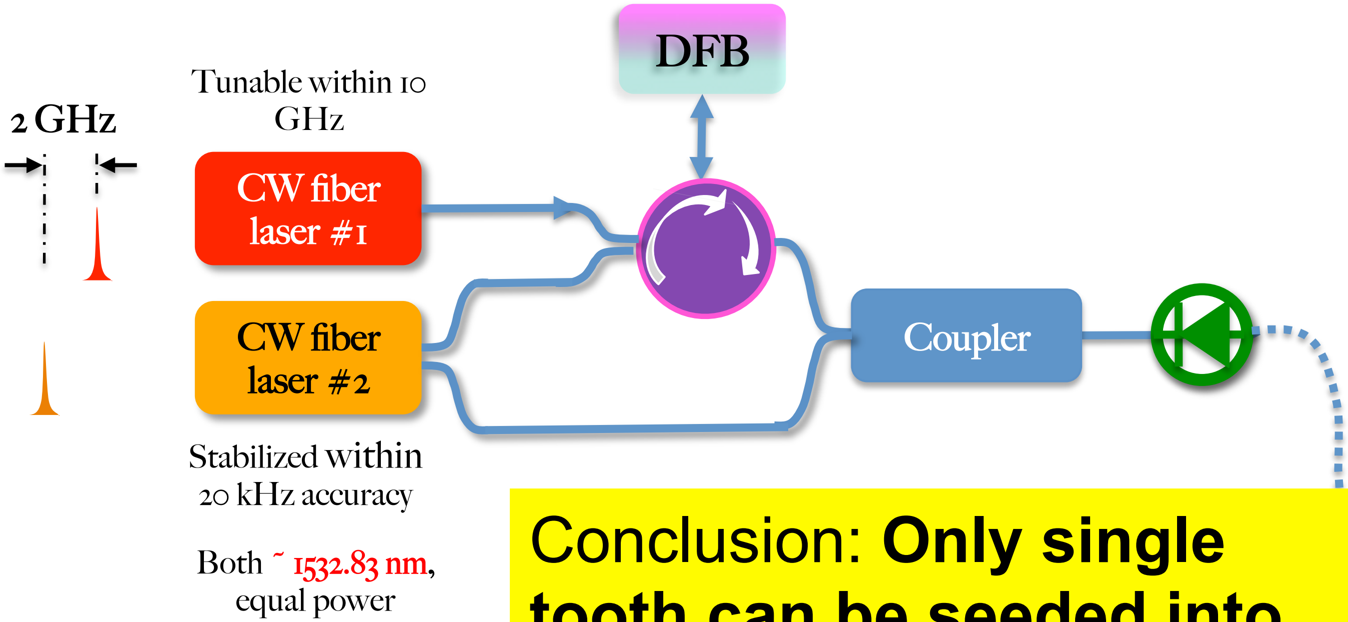
GHz comb amplification

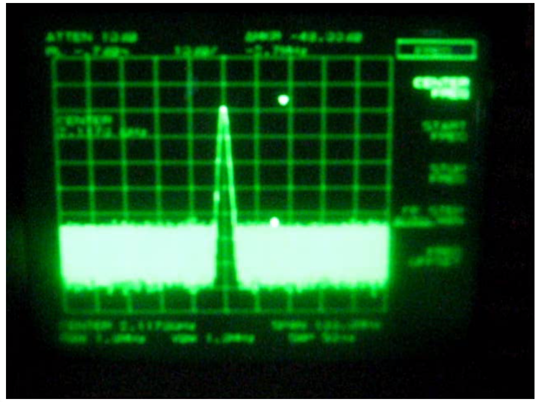
Mode competition for injection locking





unstable sub-Doppler error signal



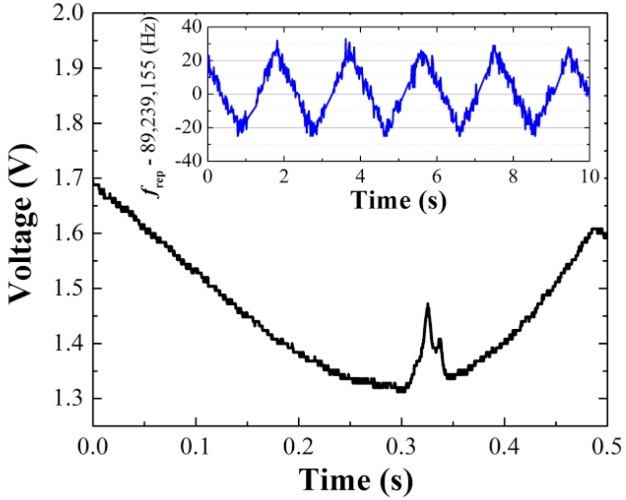


RF Spectrum Analyzer

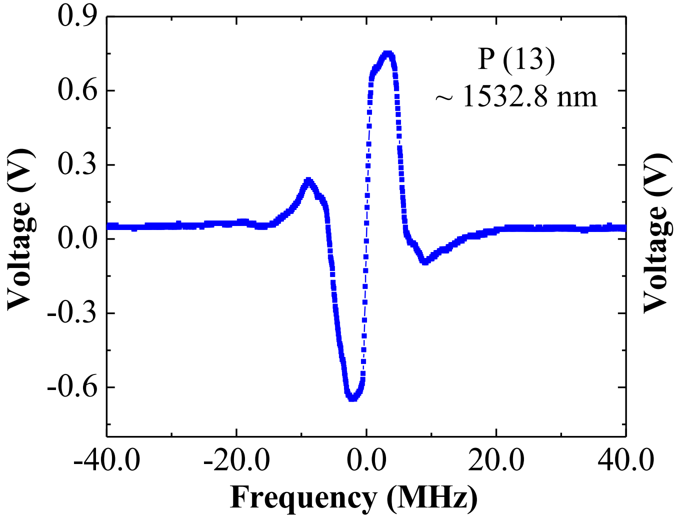
Conclusion: **Only single tooth can be seeded into DFB!**

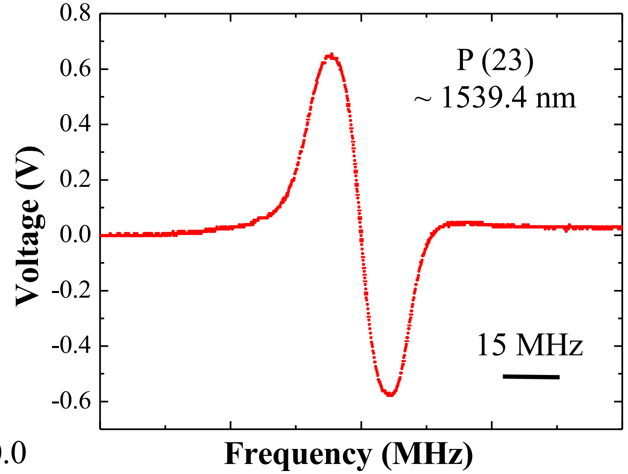
Direct optical comb locking

Sub-Doppler feature



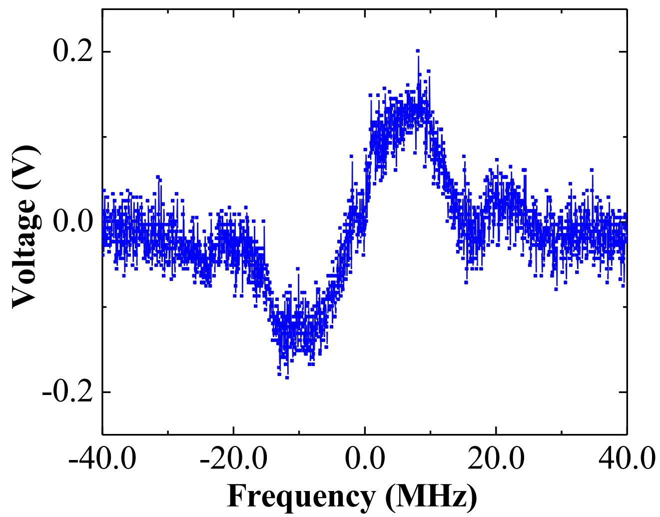
Error signals



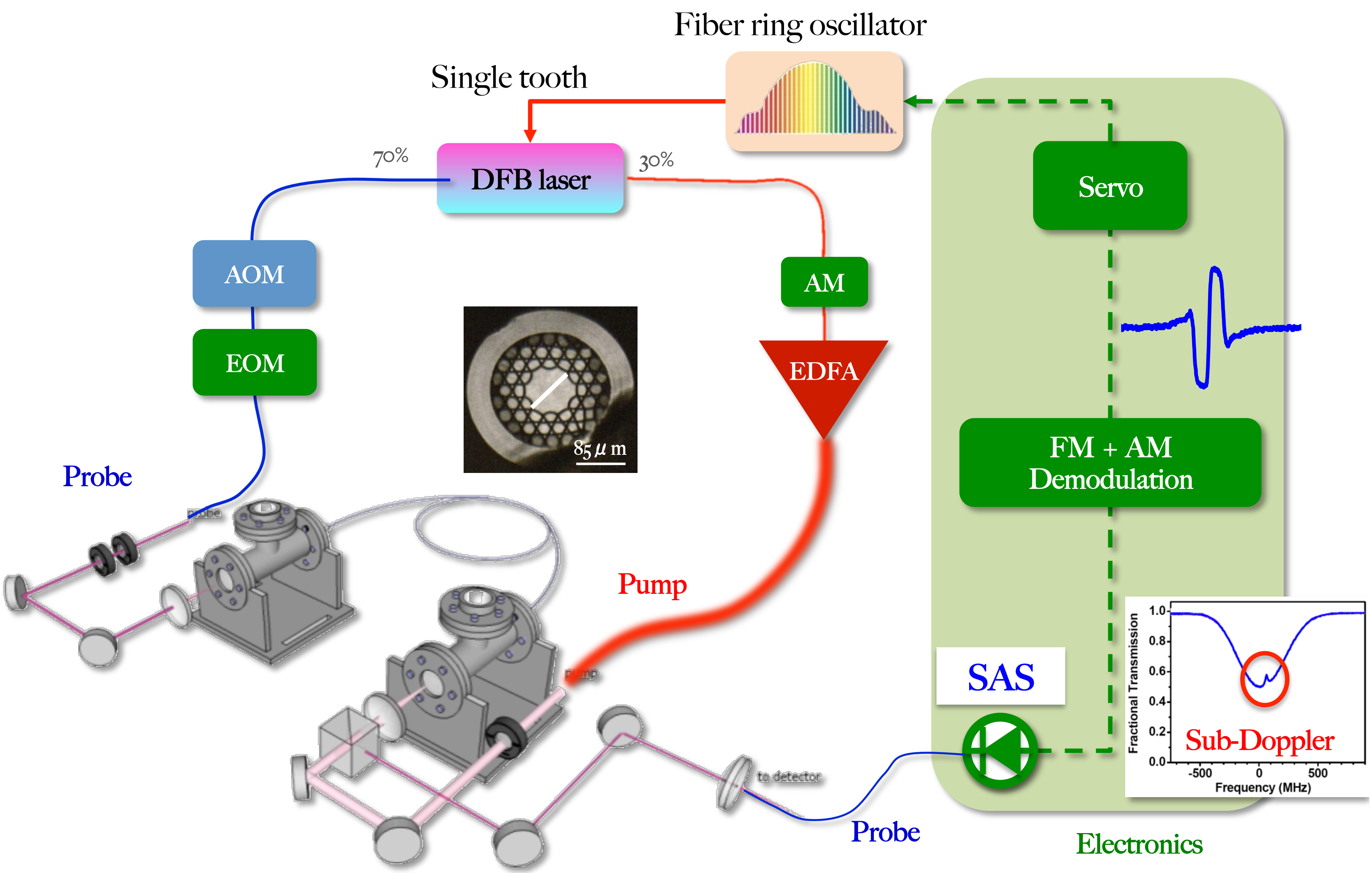


If EDFA is used
instead of
injection locking DFB laser

SAS

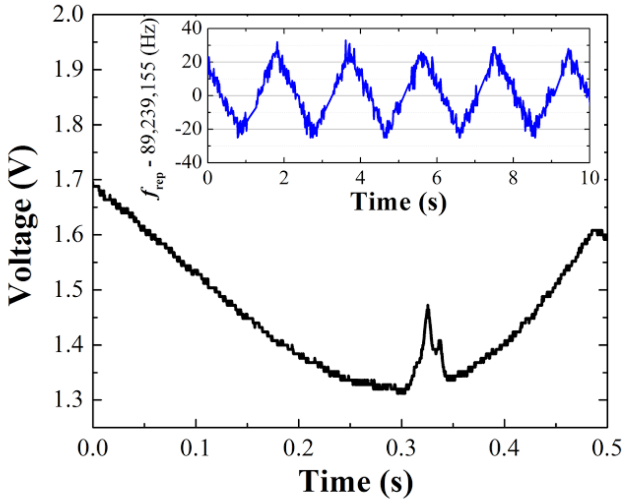


Direct optical comb locking

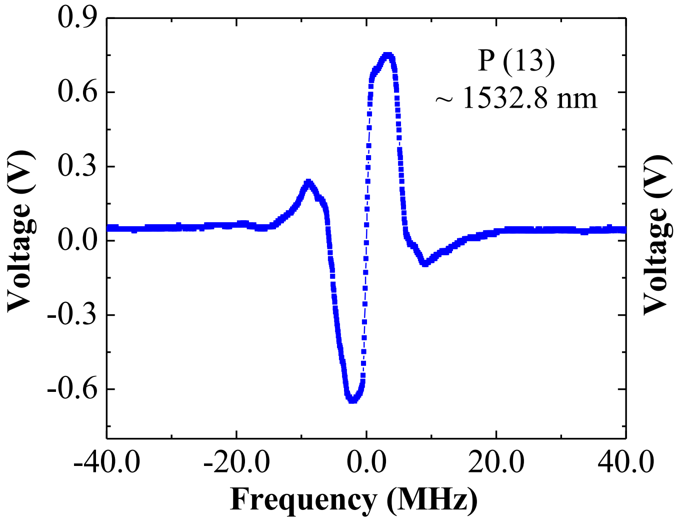


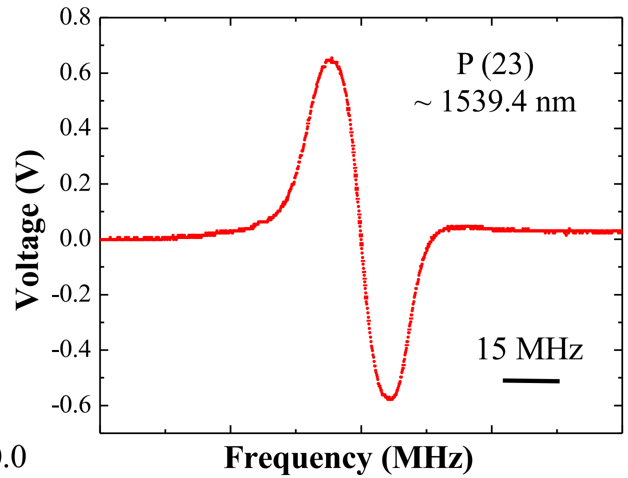
Direct optical comb locking

Sub-Doppler feature

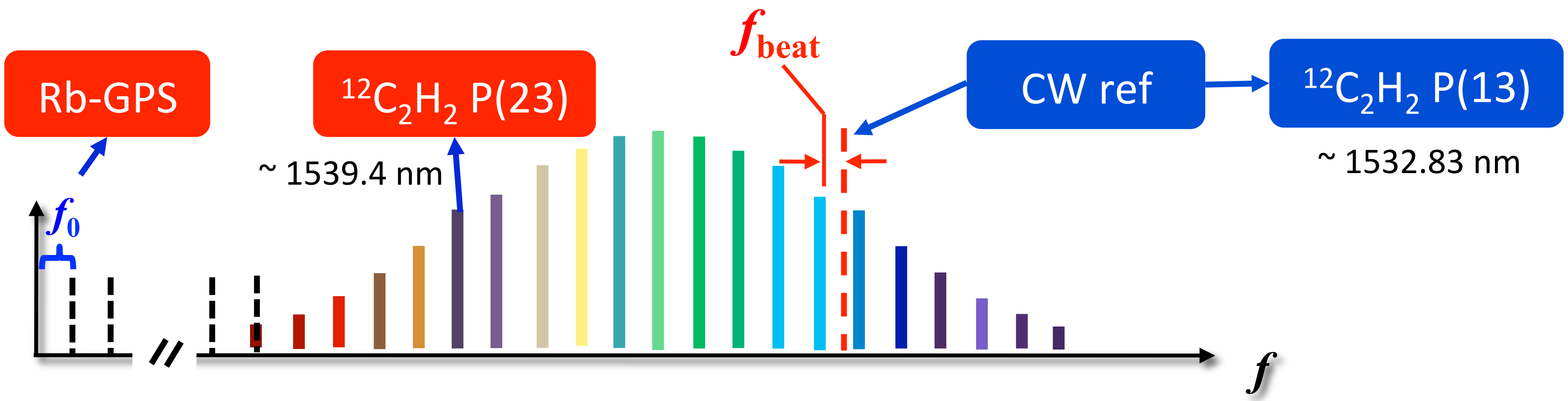


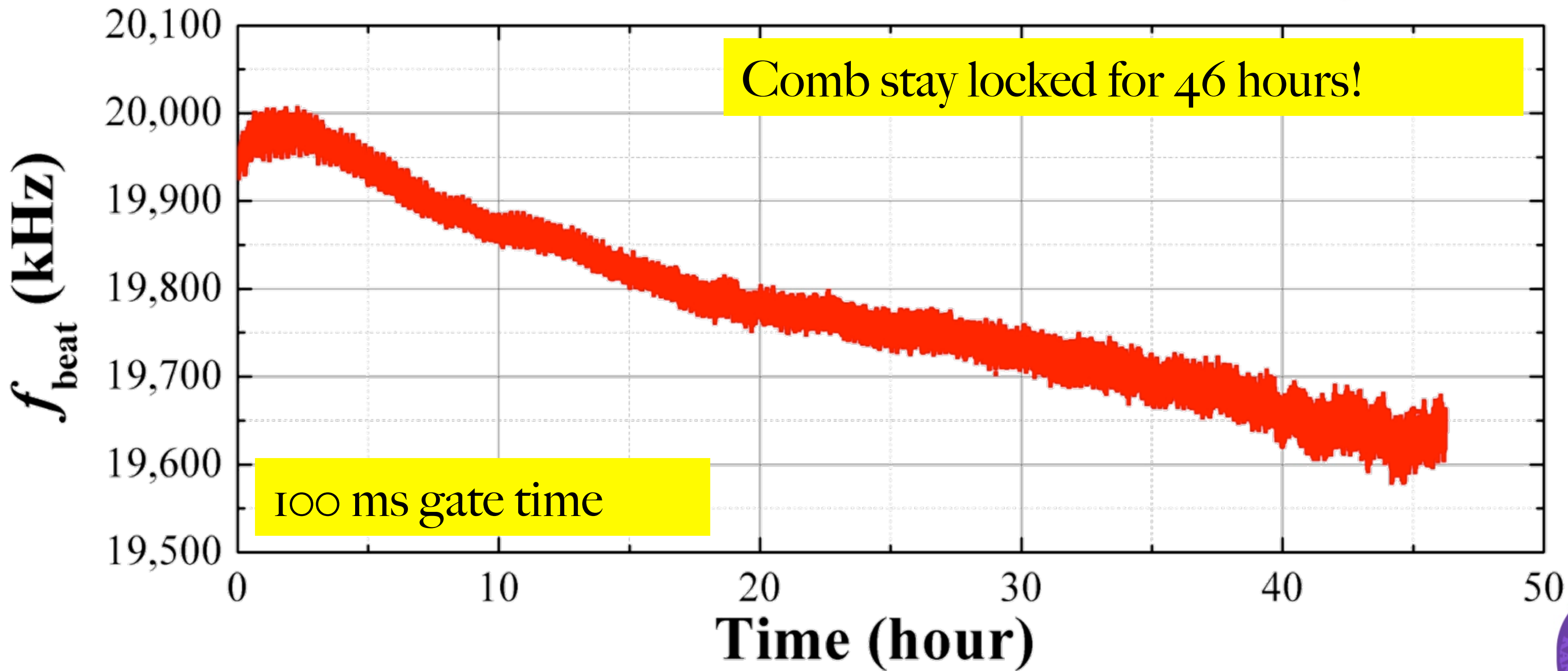
Error signals



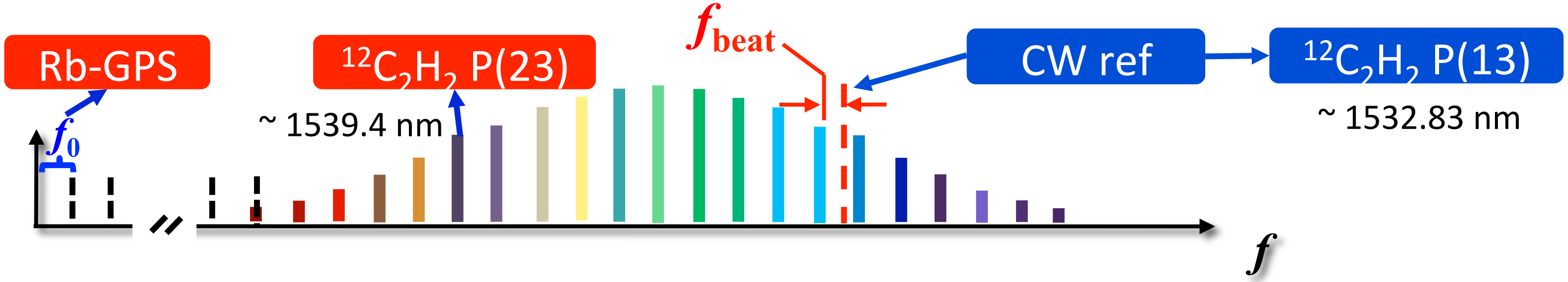


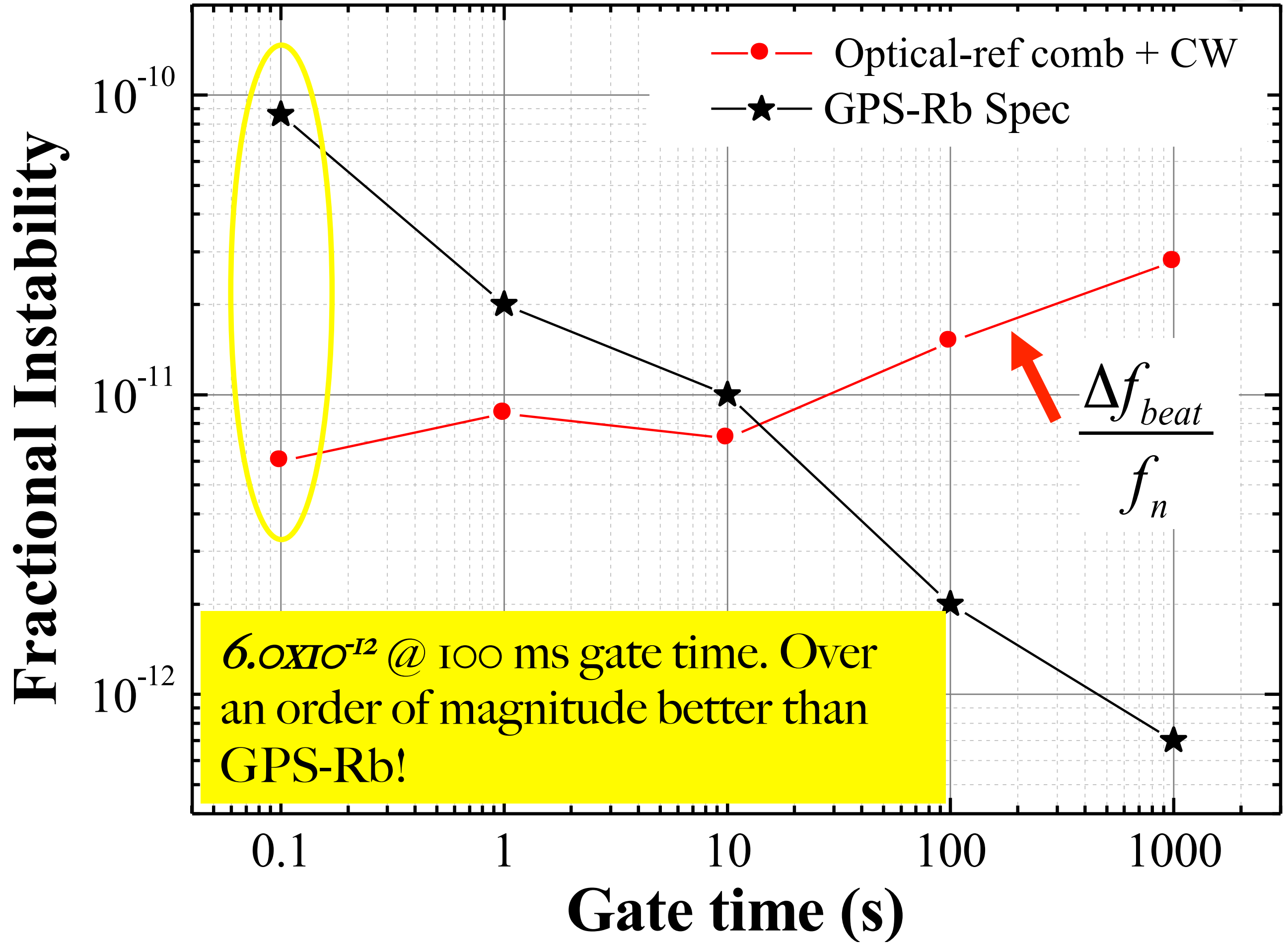
Stability measurement





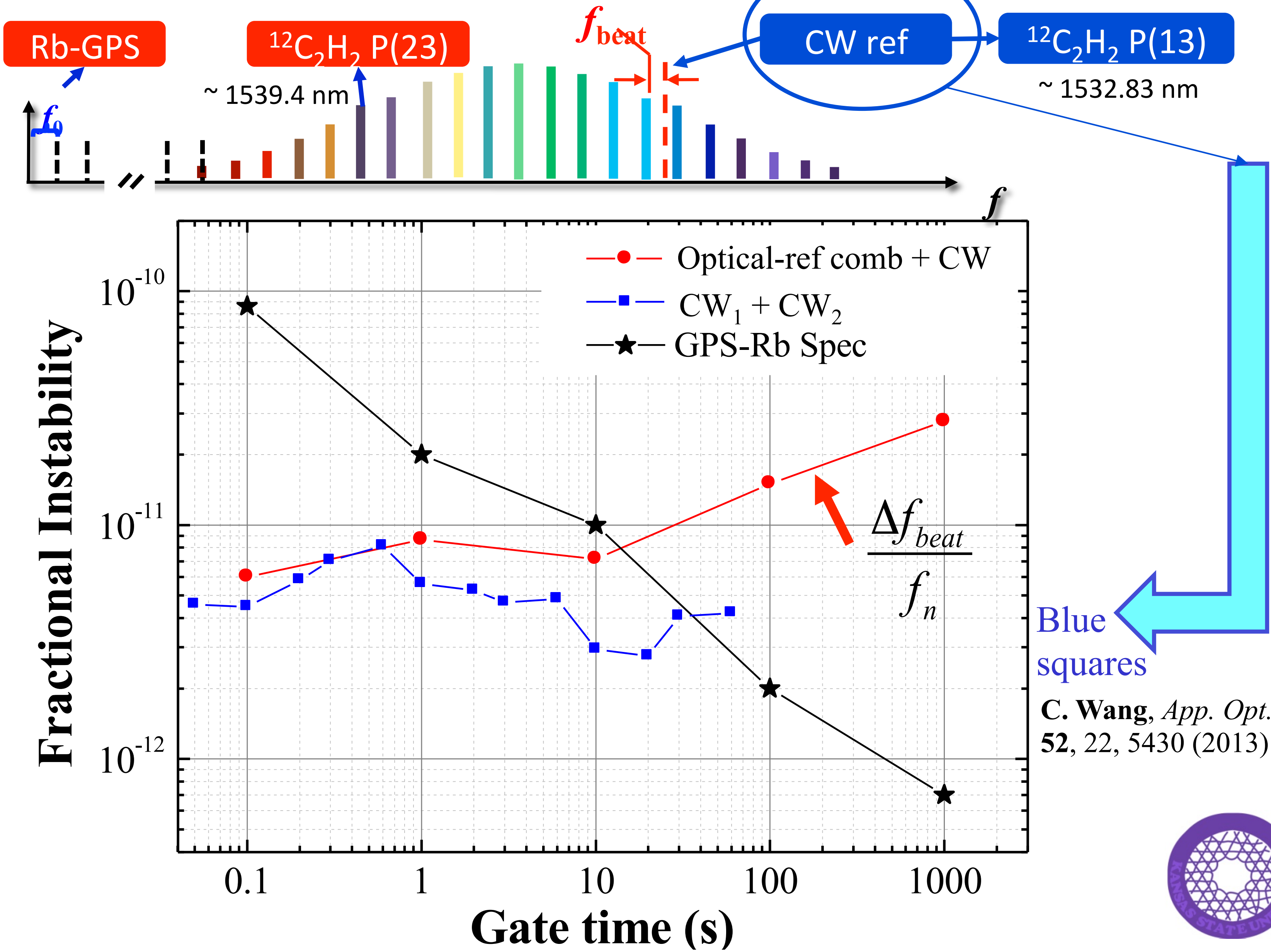
Stability measurement





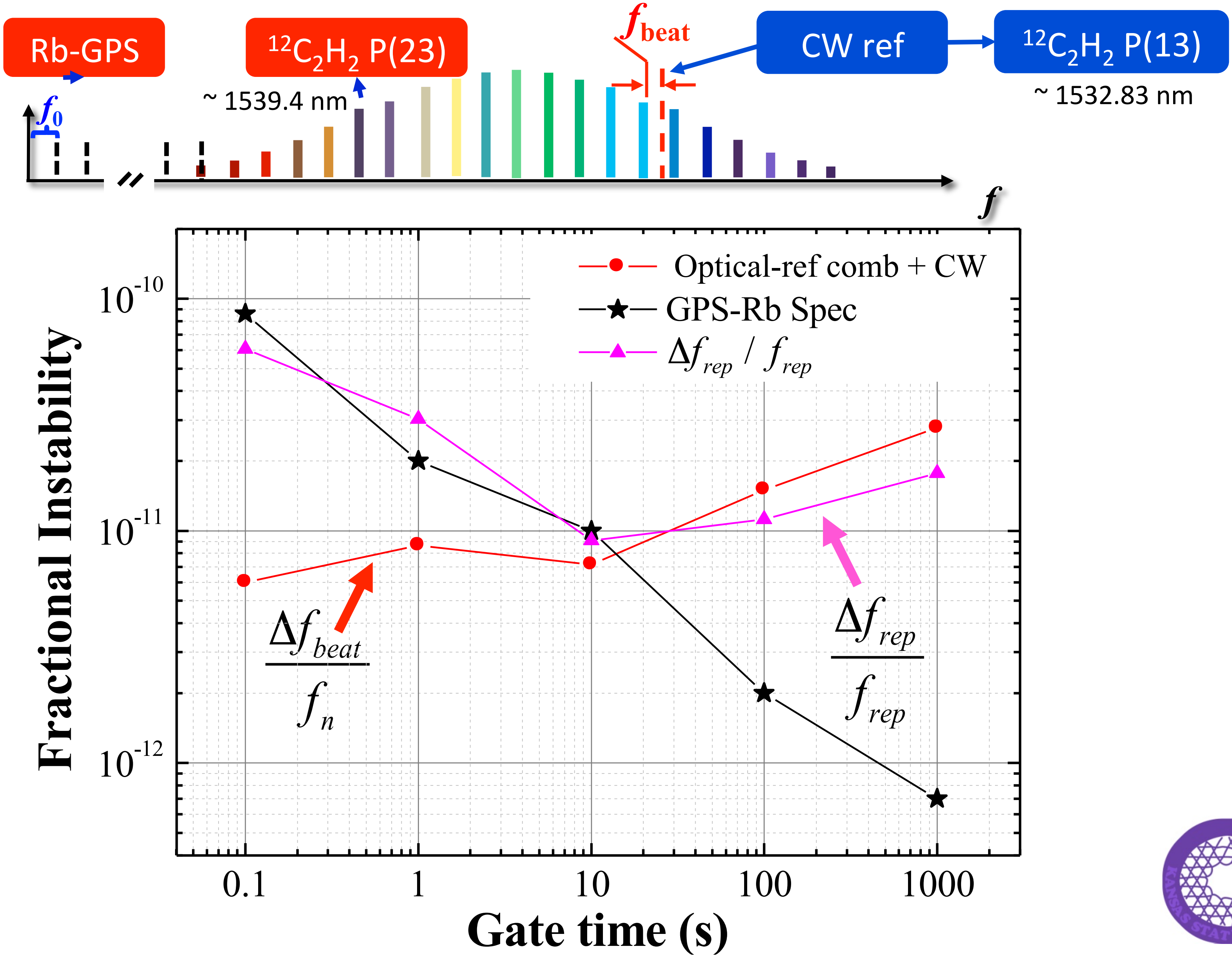
6.0x10⁻¹² @ 100 ms gate time. Over an order of magnitude better than GPS-Rb!

Compare with CW reference



C. Wang, *App. Opt.*, **52**, 22, 5430 (2013)

Microwave stability

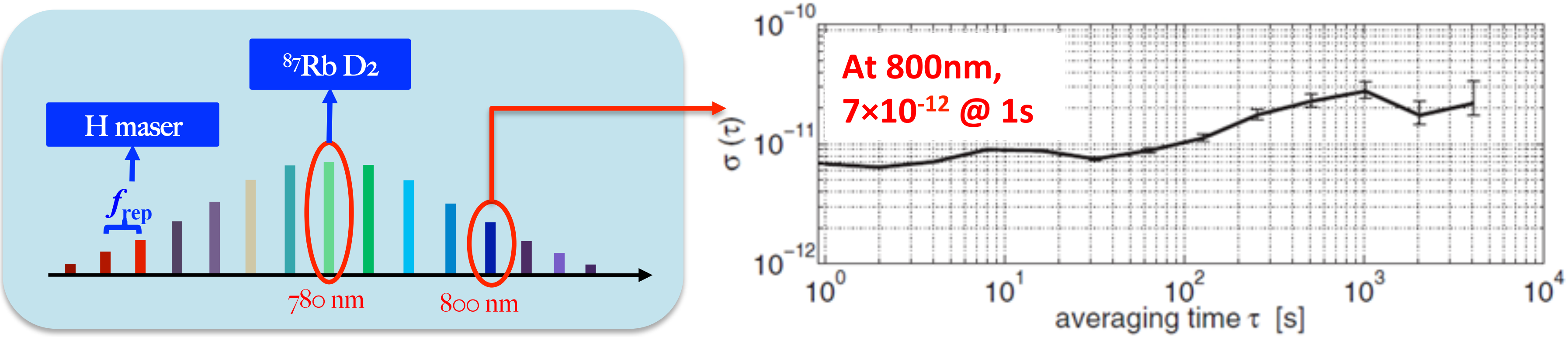


Comparable to related work

PHYSICAL REVIEW A **80**, 053806 (2009)

Optical frequency stabilization of a 10 GHz Ti:sapphire frequency comb by saturated absorption spectroscopy in ^{87}rubidium

D. C. Heinecke,[1,2,*] A. Bartels,[2,3] T. M. Fortier,[1] D. A. Braje,[1] L. Hollberg,[4] and S. A. Diddams[1,†]
[1]*National Institute of Standards and Technology, 325 Broadway M.S. 847, Boulder, Colorado 80305, USA*
[2]*Center for Applied Photonics, University of Konstanz, Universitätsstrasse 10, 78457 Konstanz, Germany*
[3]*Gigaoptics GmbH, Blarerstrasse 56, 78462 Konstanz, Germany*



- Comparable to NIST high rep rate comb
- Promising all-fiber referenced comb, especially with higher rep rate comb.

Key Points

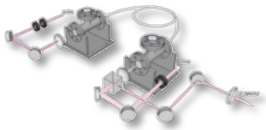
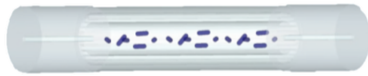
- An potentially all-fiber portable comb is demonstrated via:
  - Direct stabilization:

1) single tooth isolated and amplified to > 40 mW, high fidelity. (power amplification of 10^6)

2) comb locked directly to an acetylene transition at 1539.4 nm (f_o to modestly stable rf source).

- 7 nm away from the fixed tooth (at 1532.8 nm) shows fractional instability of 6×10^{-12} at 100 ms gate time, over an order of magnitude better than GPS-Rb.
  - Stability of the optical reference is well transferred to the measured tooth.
- **Gas-filled fibers suitable for directly referencing GHz combs without ultrastable rf.**

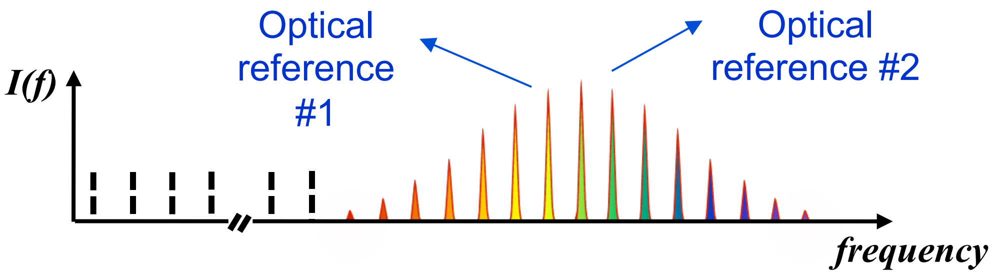
Future directions

- Improve long term stability.
- Replace Fabry-Perot cavity with a high rep rate fiber comb.
- Replace  by 

Acetylene fiber-cell reference

Improve portability

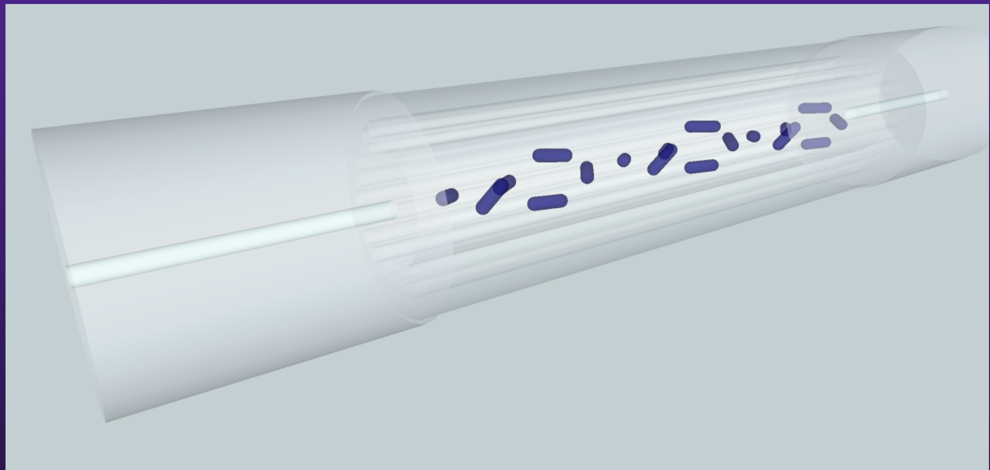
- Alternate locking scheme



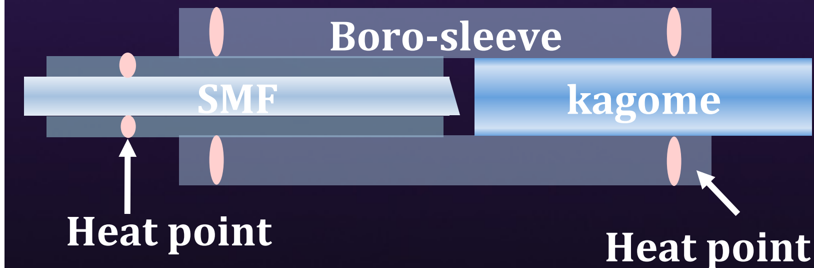
Challenge:

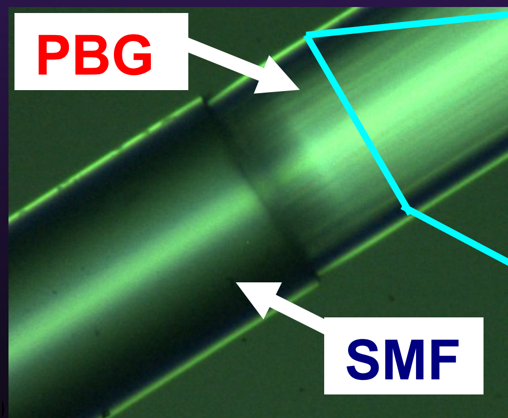
- Two comb teeth needs to be at least 100 nm apart to avoid fast degradation over large spectral bandwidth.

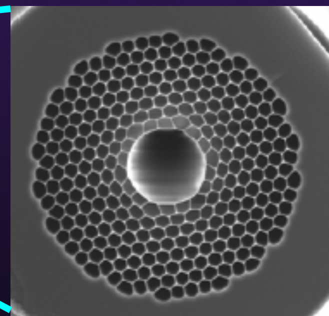
Sealed Photonic Microcells as references



K-State Spliced Fiber (2005)





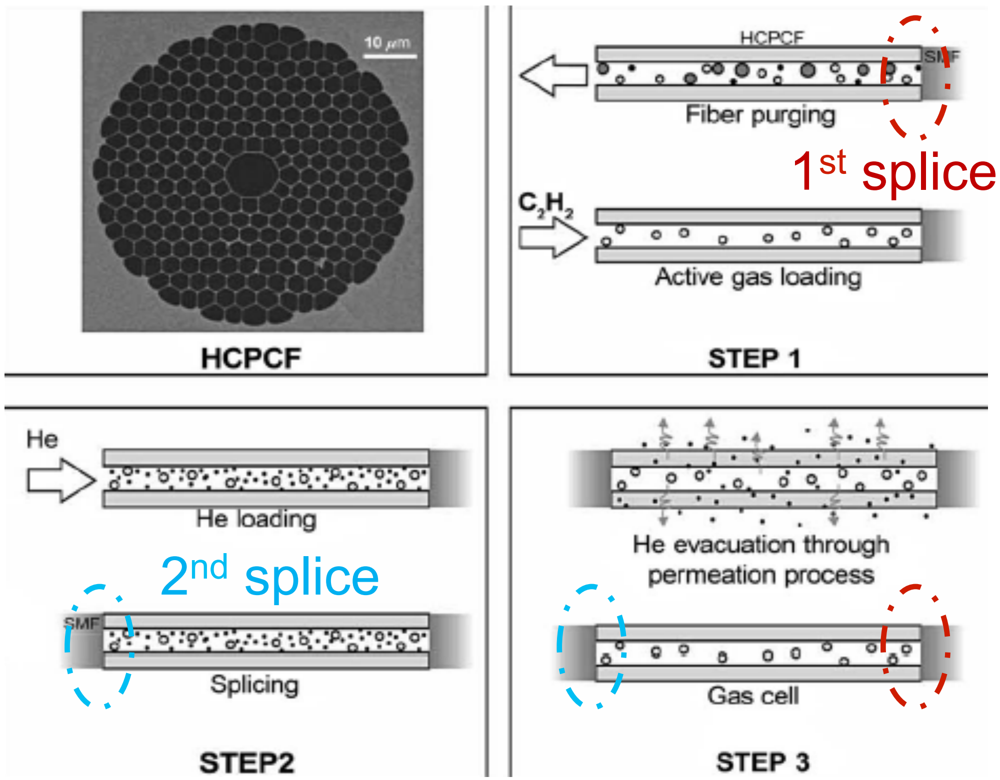


lice Loss ~ 1.4 dB

Electric Arc Splicer

Sealing gas inside fibers

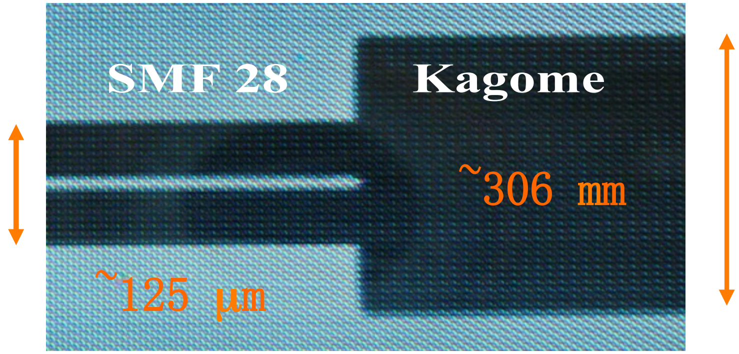
- **Trapping gas during splice**

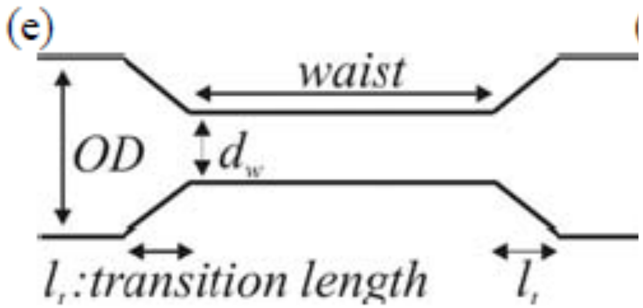


Light , et. al., University of Bath, *Opt. Let.* 31, 2538 (2006).

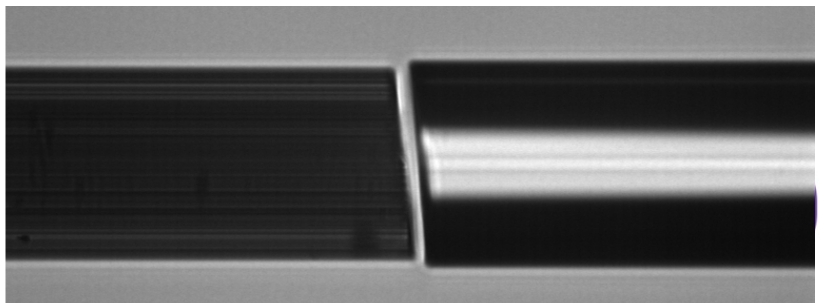
Splice reflections:“angle splice”

- **Size mismatch**

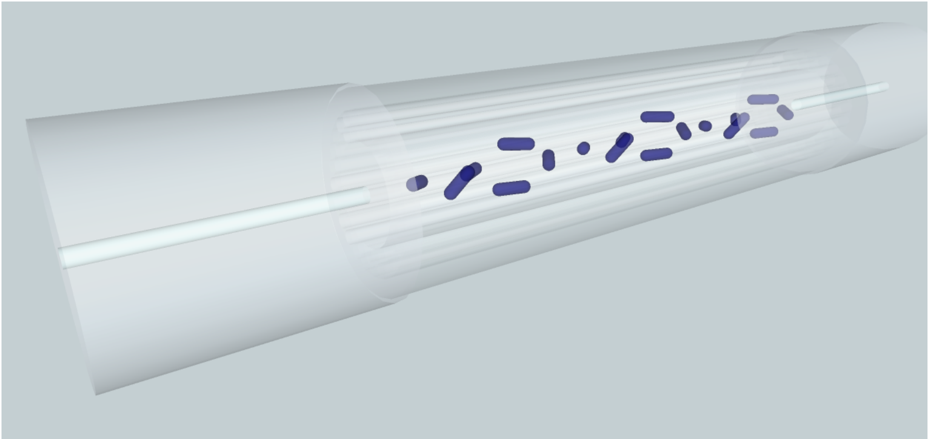




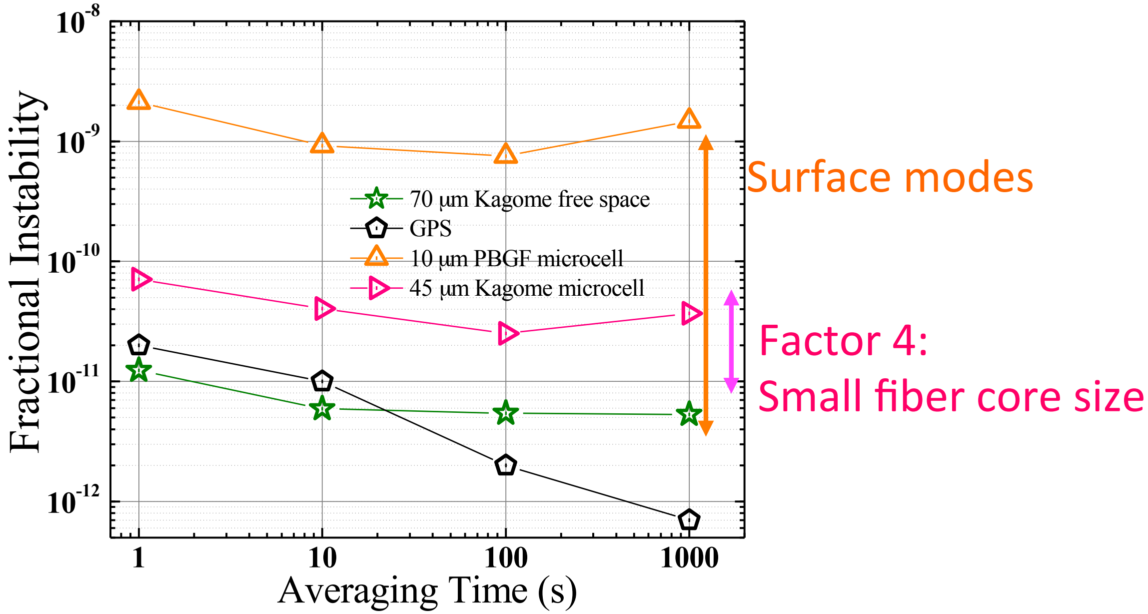
Different outer diameters of fiber core

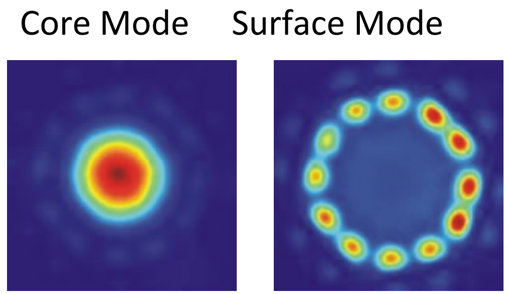


Sealed photonic microcell frequency references



- **Fabricated with ~11% transmission**
- **tested over 2 years; small (factor 2)SNR degradation over 1-2 years**
- **Within order of magnitude of VC reference**

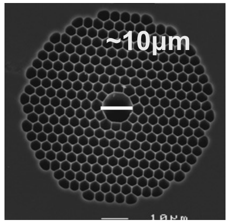




Smith, West, *et al.* Nature (2003)

TWO PHOTONIC MICROCELLS

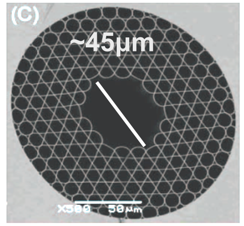
PBGF



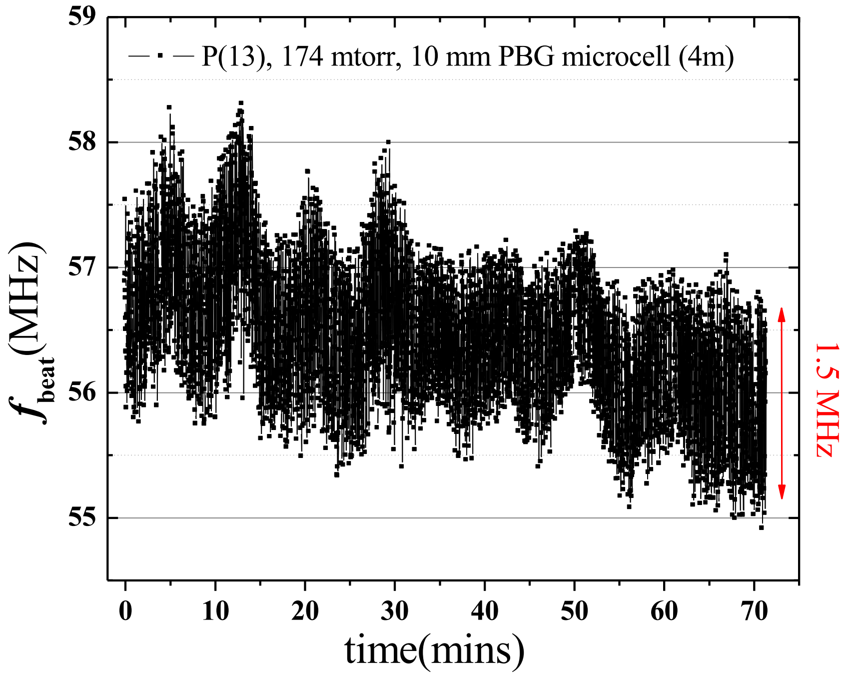
Fiber length: 4 m
C_2H_2 pressure of 174 mtorr

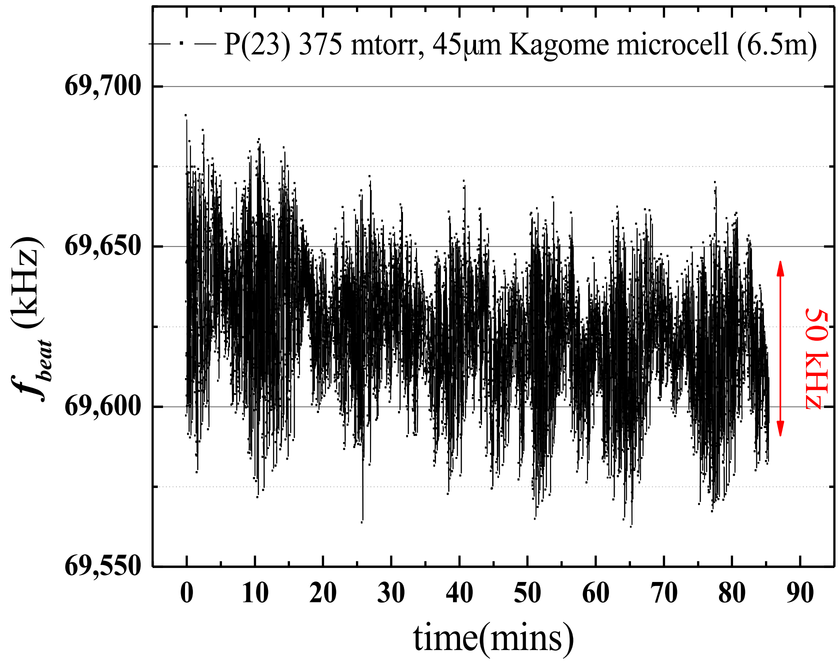
kagome

Fiber length: 6.5 m
C_2H_2 pressure of 375 mtorr



N. V. Wheeler, *et. al.* ,***CLEO***, CTuS5, San Jose, CA (2010)

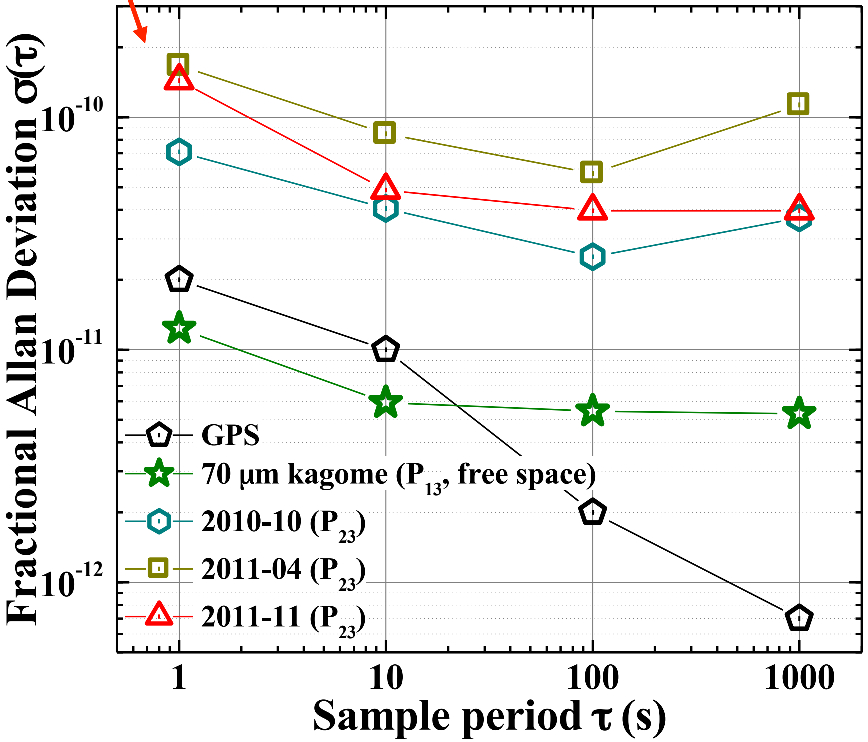


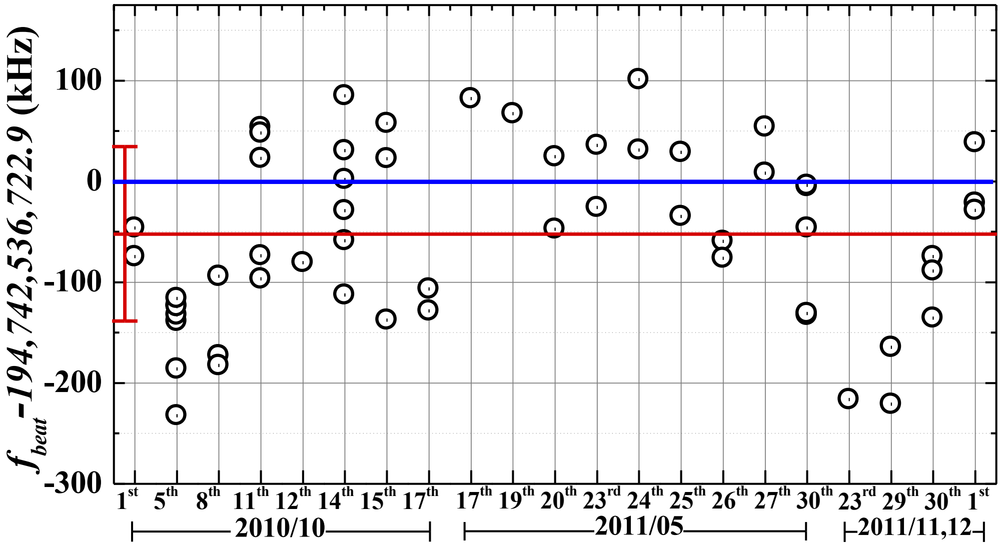


Photonic Microcell - Performance

no further degradation

long-term stability is improved by using a PM EDFA





σ = 86 kHz,
3σ=258 kHz

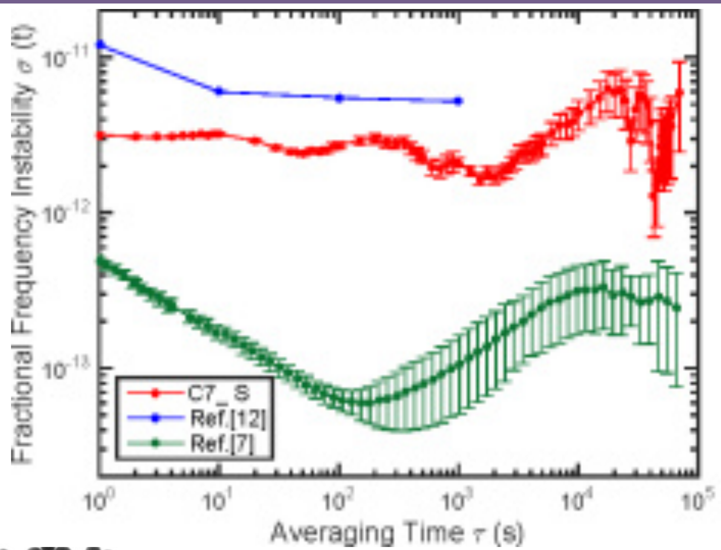
Repeatability within ±200 kHz

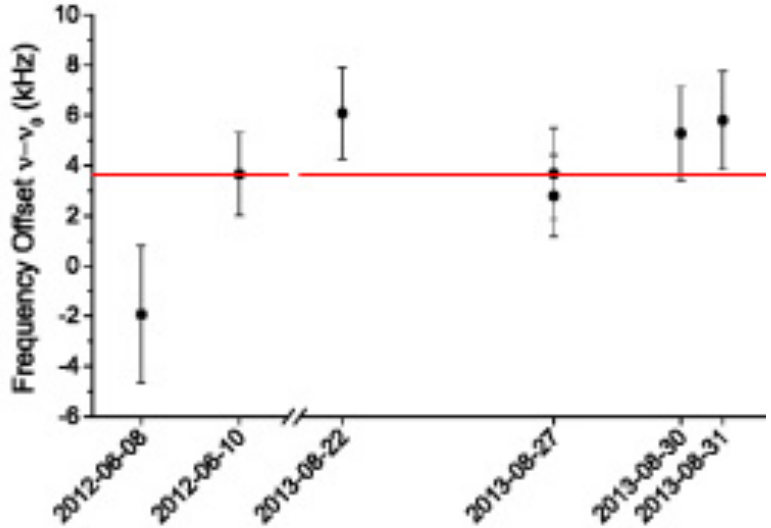
Accurate (~10^{-10}) all-fiber optical frequency reference does not require alignment!!

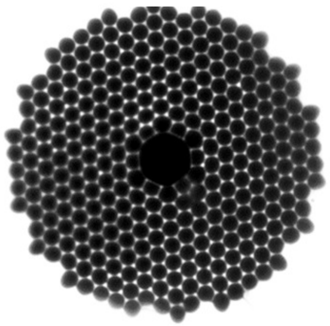
Experimentally measured absolute frequency of the P(23) $\nu_1 + \nu_3$ transition in $^{12}C_2H_2$ over 1 year.

Optical frequency standard using acetylene-filled hollow-core photonic crystal fibers

Marco Triches, Mattia Michieletto, Jan Hald, Jens K. Lyngsø, Jesper Lægsgaard, and Ole Bang



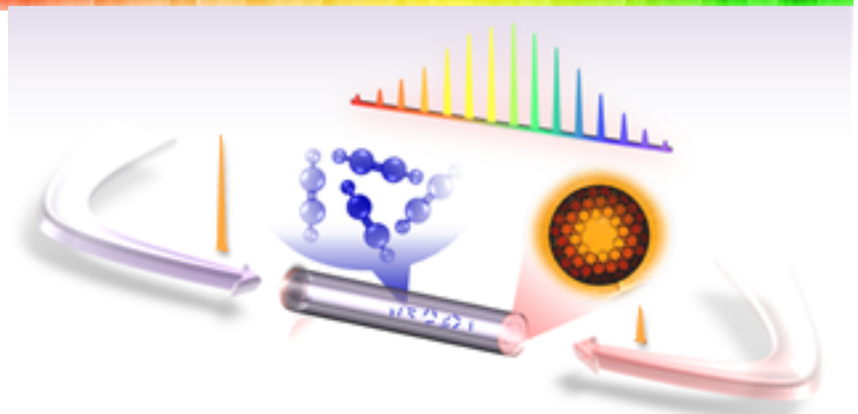




Left: Summary of the performance achieved using the C7_S fiber in a temperature stabilized environment (red). The system is compared with the reference laser [7] stabilized to a bulk glass cell (green) and with the best performance reported in [12] for an gas-filled HC-fiber stabilized laser (blue). Right: The lock-point repeatability over 7 measurements. The error bars represent the root mean square value of the measured data

Marco Triches, Mattia Michieletto, Jan Hald, Jens K. Lyngsø, Jesper Lægsgaard, and Ole Bang, "Optical frequency standard using acetylene-filled hollow-core photonic crystal fibers," Opt. Express **23**, 11227-11241 (2015)

Summary



- Microstructured optical fiber
  - Revolutionary technology

- Sub-Doppler gas-filled fiber references promising and improving technology

- Direct comb stabilization to gas-filled fiber
  - 6×10^{-12} stability at 100 ms
  - Single tooth amplification to >40 mW demonstrated, preserving SNR
  - Promising for direct optical stabilization of any GHz comb
- Mid-IR ns lasers improving

Left out:

- *CW low Quantum defect lasers*
  - *Active research area*


Thank You!

KANSAS STATE UNIVERSITY