Ultrafast Dynamics and Precision Stabilization in Chip-Scale Optical Frequency Combs

Presented by:

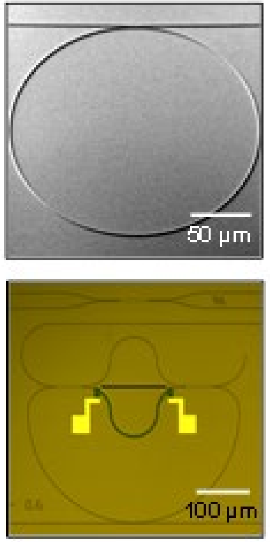
OSA Integrated Optics Technical Group

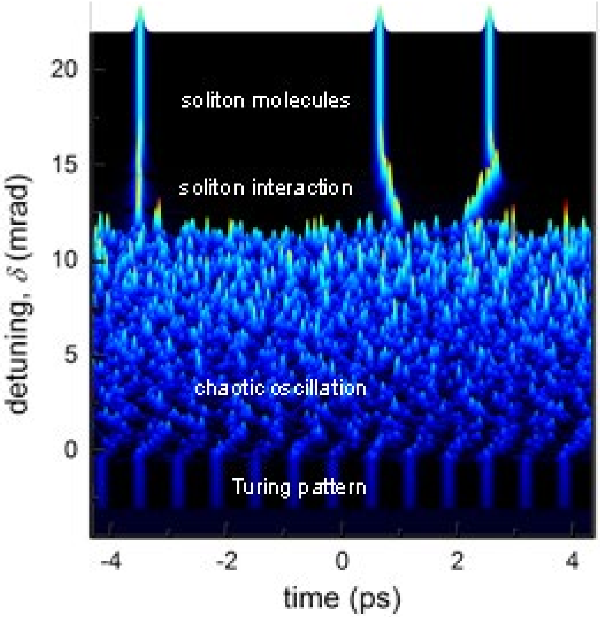
Integrated
Optics
Technical Group

Welcome to Today's Webinar

"Ultrafast Dynamics and Precision Stabilization in Chip-Scale Optical Frequency Combs"

Dr. Shu-Wei Huang, UCLA





Organized by Integrated Optics Technical Group

Integrated Optics Technical Group

Technical Group Committee

Kensuke Ogawa
Fujikura
Chair

Mark Pelusi
Univ. of Sydney
Vice Co-chair,
Event Officer

Satoshi Iwamoto
Univ. of Tokyo
Vice Co-chair

Dawn Tan
Singapore Univ. of
Technology and Design
Webinar Officer

Contact the Committee for an opportunity as a Social Media Officer.

Integrated Optics Technical Group

Scope of the Technical Group

- The integration of optical components to perform various functions such as WDM, optical signal processing, etc.
  - Technology platforms
    - Compound semiconductor photonics
    - Silicon photonics
    - Polymer photonics

Home / Get Involved / Technical Divisions / Photonics and Opto-Electronics

Integrated Optics (PI)

www.osa.org/IntegratedOpticsTG

- TG members involved as session co-chairs in the upcoming meetings

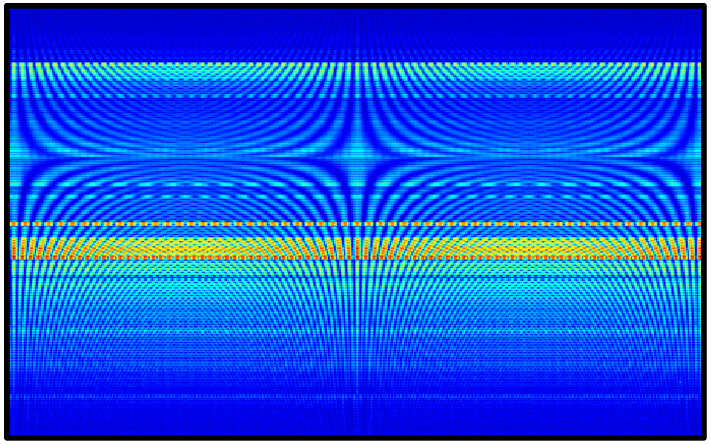
ICO-24 JAPAN TOKYO 2017

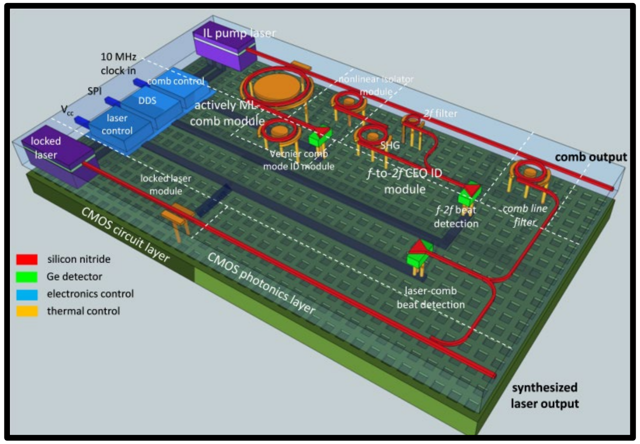
The 24th Congress of the International Commission for Optics

Date 21 (Mon) - 25 (Fri) August 2017 | Venue : Keio Plaza Hotel, Tokyo

Get involved with your suggestion of invited speaker candidates!

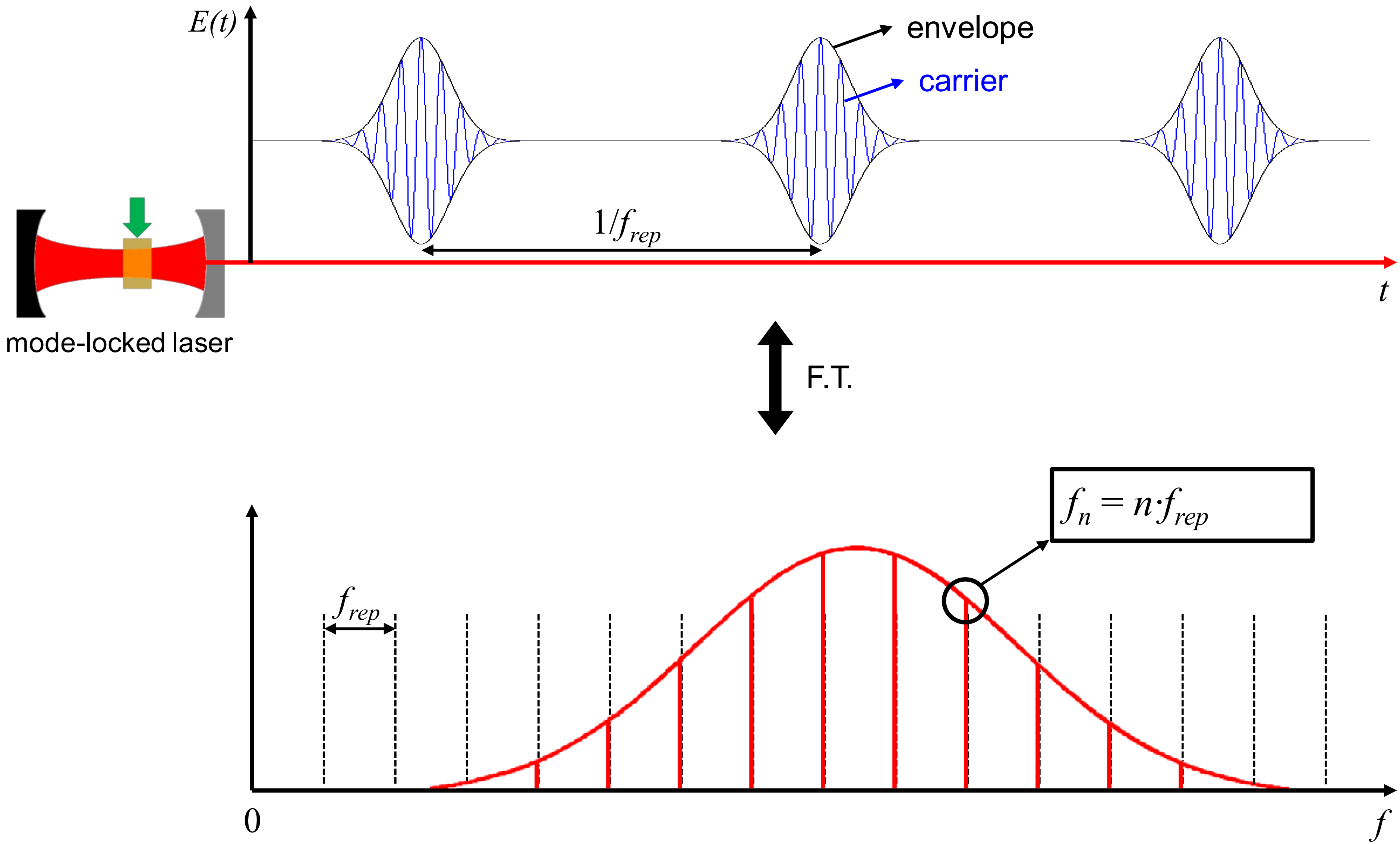
Ultrafast dynamics and precision stabilization in chip-scale optical frequency combs



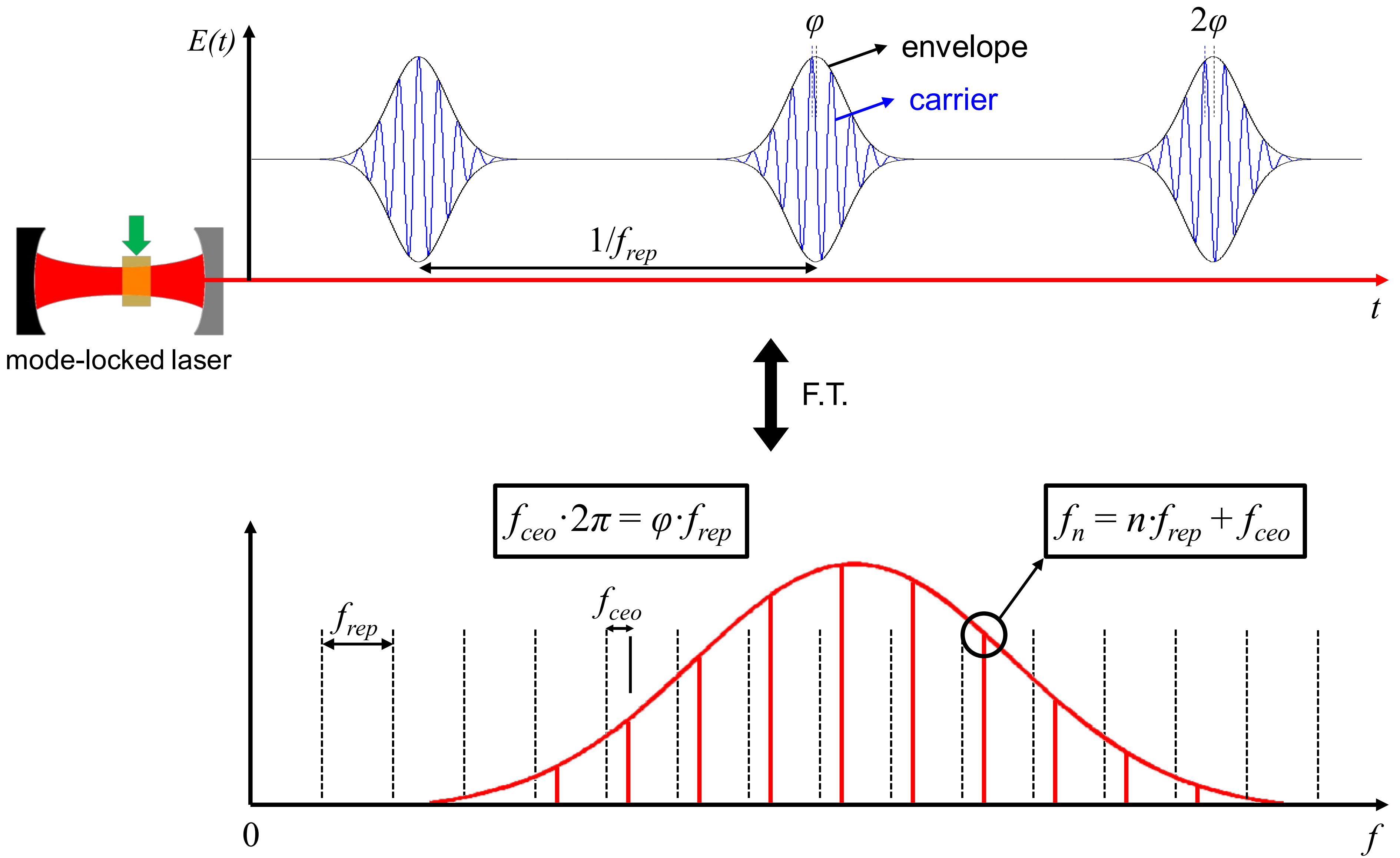


Shu-Wei Huang
University of California Los Angeles

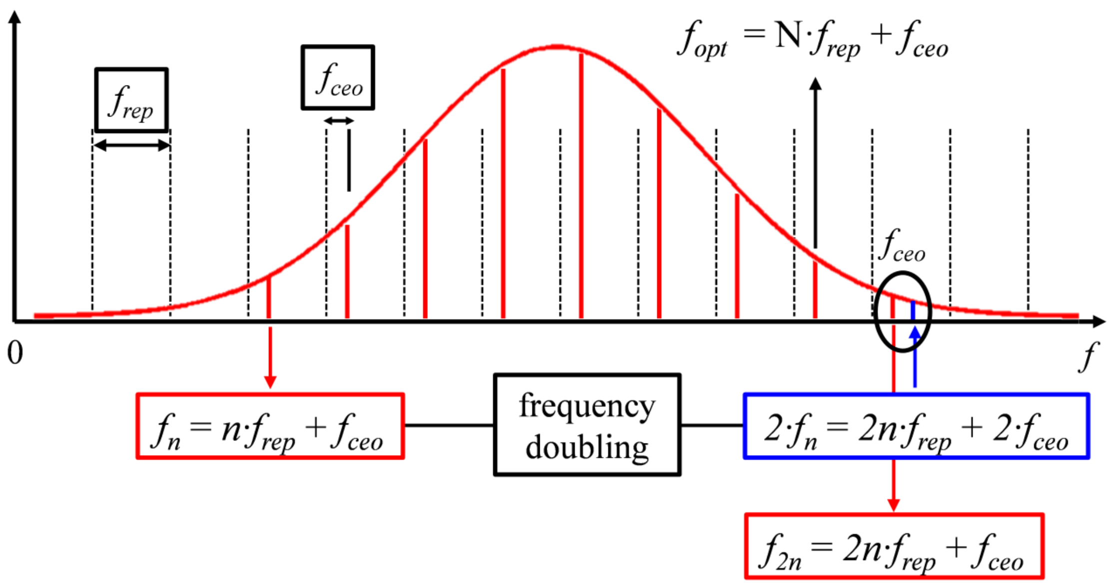
Optical Frequency Comb

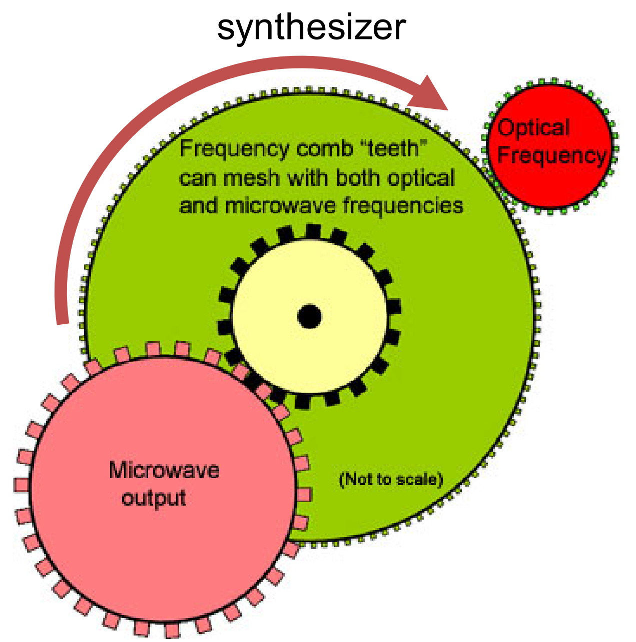


Optical Frequency Comb



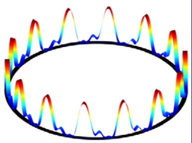
An elegant way to link electronics with optics



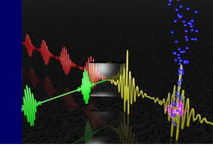


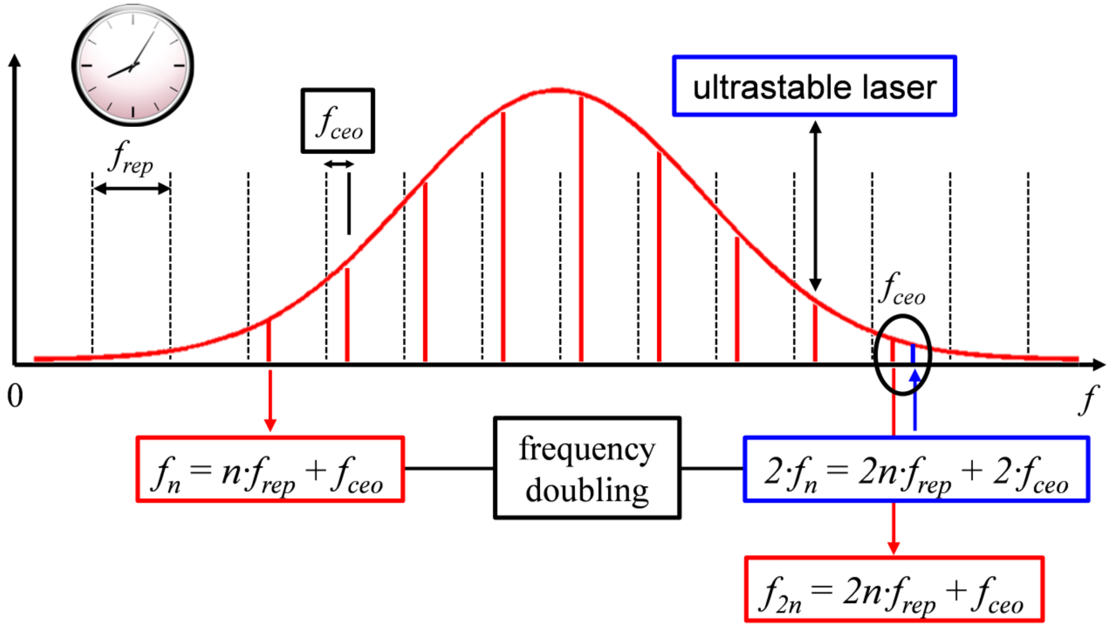
NIST

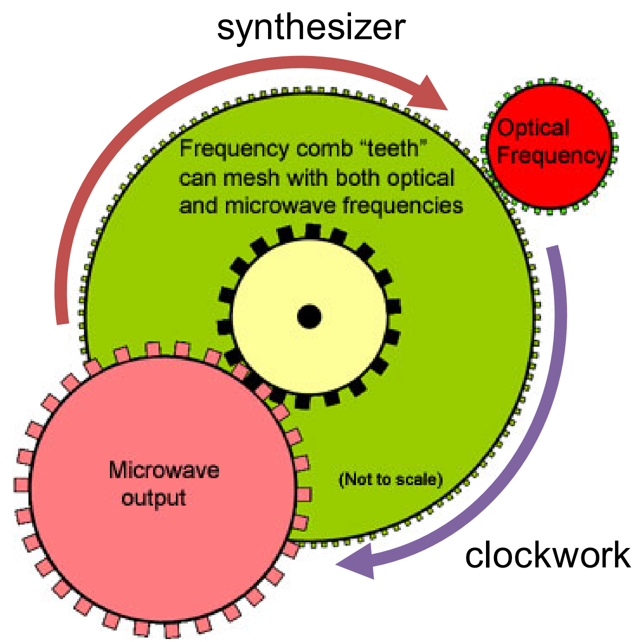
1. Locking both f_{rep} and f_{ceo} to electronic oscillators leads to accurate evaluation of optical frequencies.



An elegant way to link electronics with optics

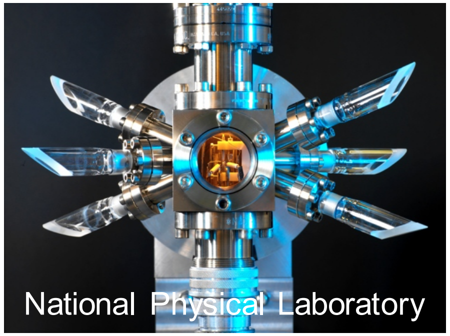




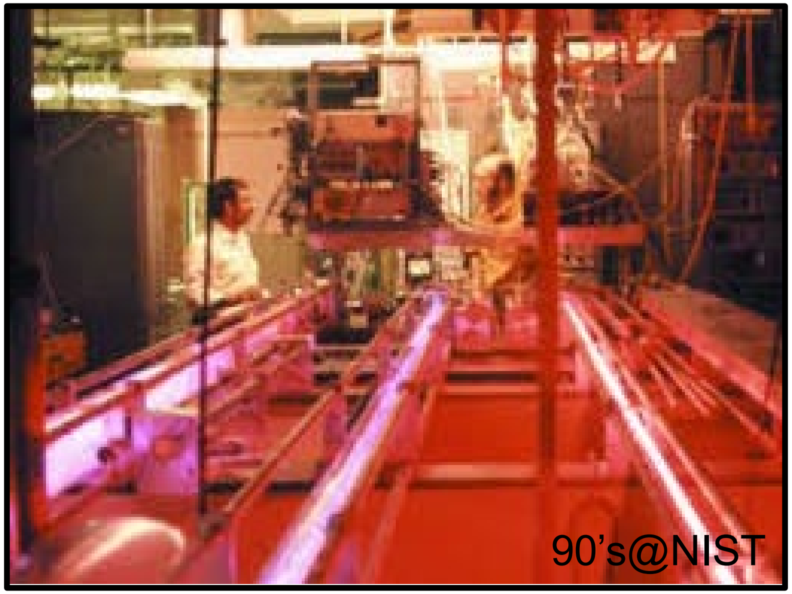


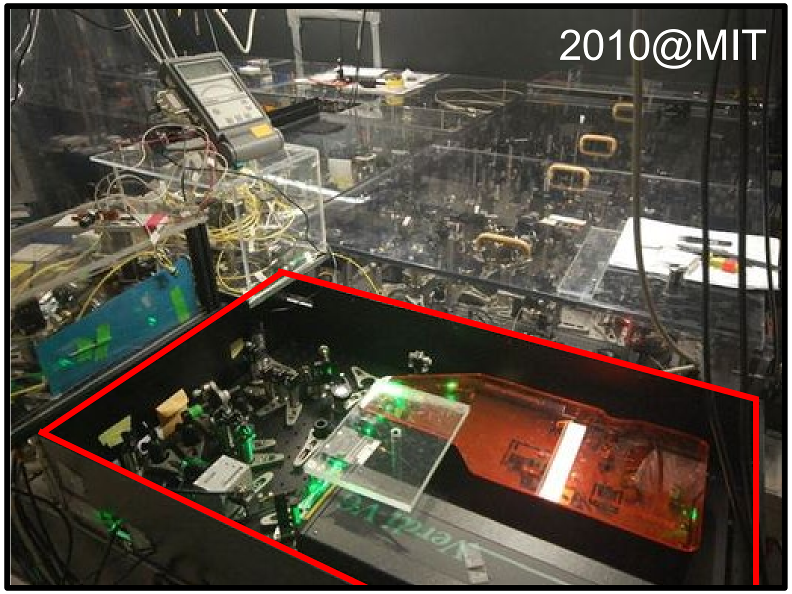
NIST

1. Locking both f_{rep} and f_{ceo} to electronic oscillators leads to accurate evaluation of optical frequencies.
2. Locking f_{opt} to an ultrastable laser and f_{ceo} to an electronic oscillator lead to the next time standard.

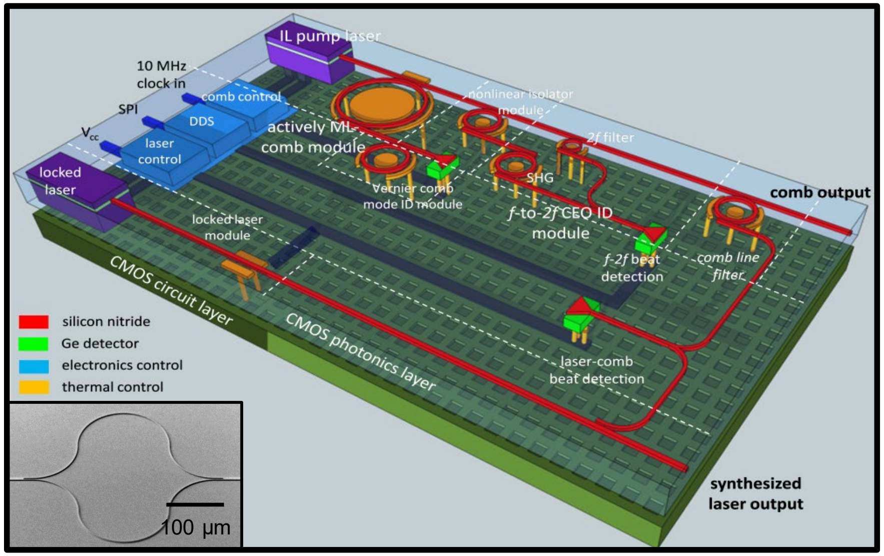


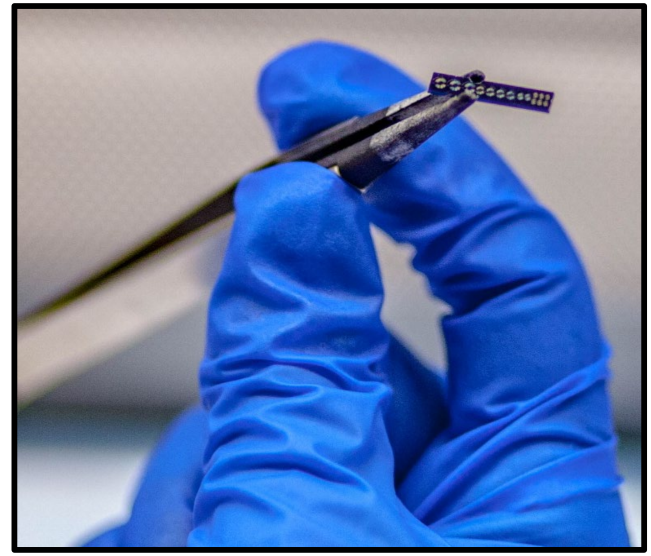
Frontier of frequency metrology





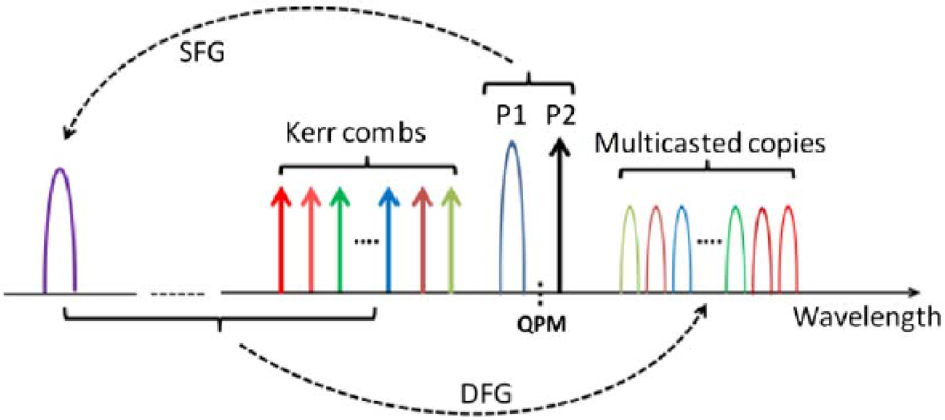
Chip-scale Optical Frequency Comb





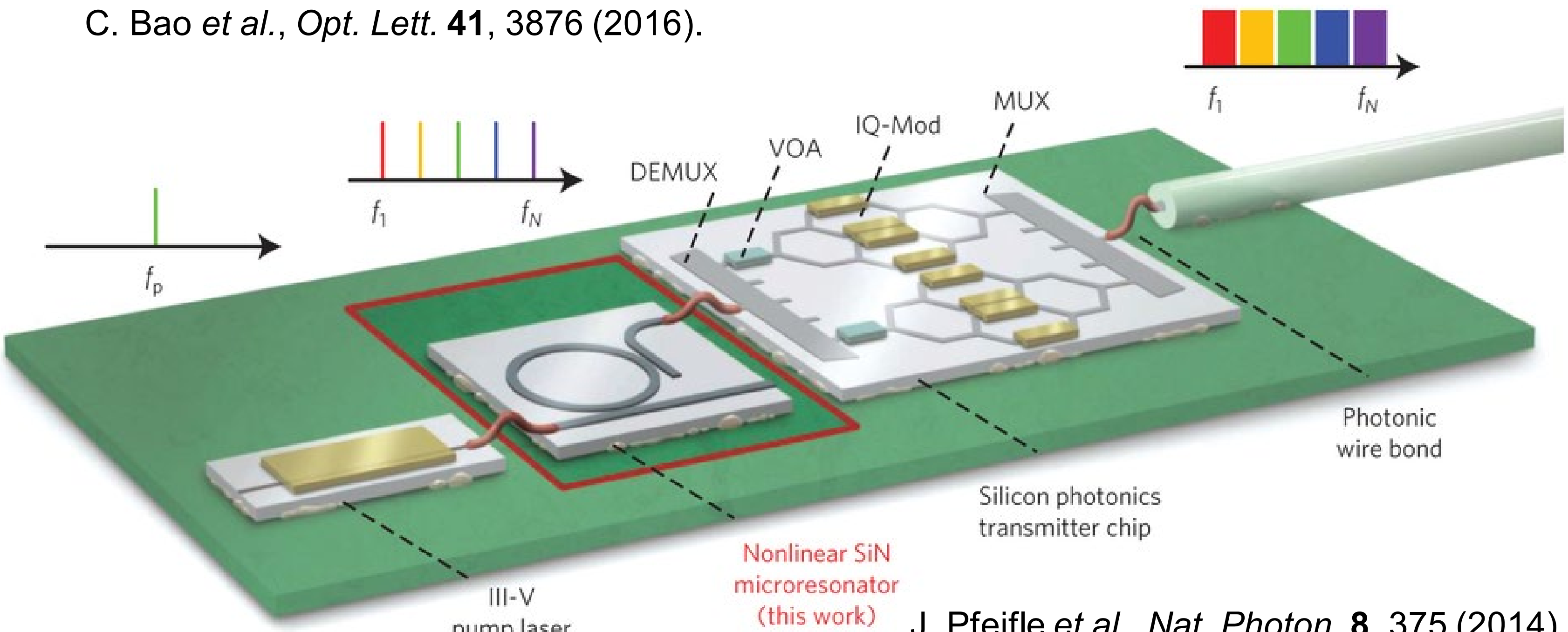
1. Microresonator-based ultrafast light source delivering 74 femtosecond pulse train
   - Huang *et al.*, *Phys. Rev. Lett.* **114**, 053901 (2015).
2. Low noise broadband microcomb containing 3,600 coherent frequency teeth
   - Huang *et al.*, *Sci. Rep.* **5**, 13355 (2015).
3. High bandwidth comb stabilization achieving a fractional uncertainty of 2.7×10^{-16}
   - Huang *et al.*, *Sci. Adv.* **2**, e1501489 (2016).
4. Microresonator stabilized diode laser at the thermodynamical limit of 1.7×10^{-13}
   - Lim *et al.*, *Opt. Lett.* **41**, 3706 (2016).

Terabit optical telecommunications



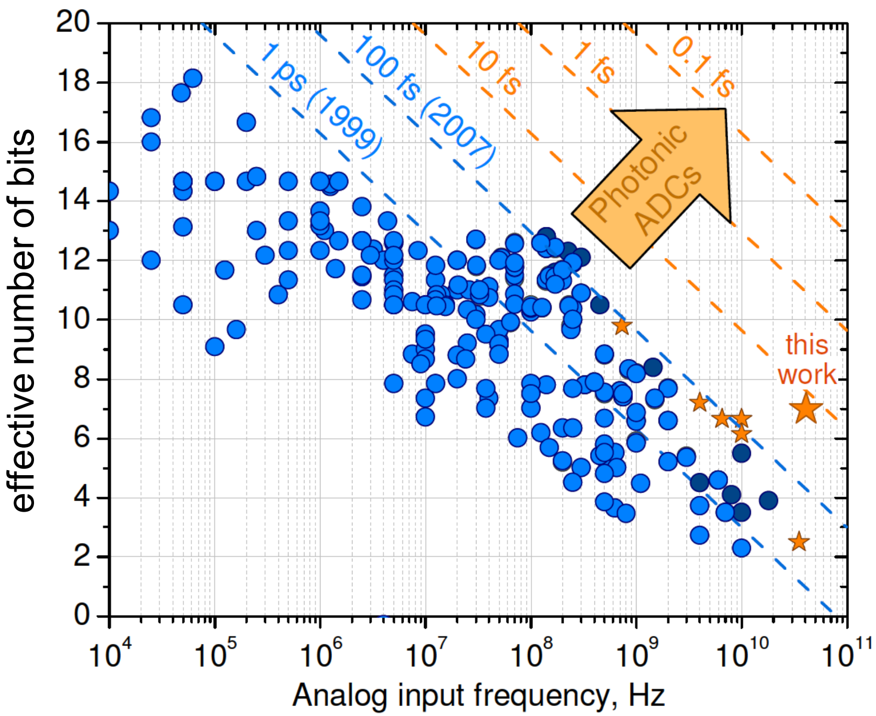
"The combination of chip-scale Kerr frequency comb sources with large-scale silicon photonic integration can become a key concept for power-efficient optical interconnects."

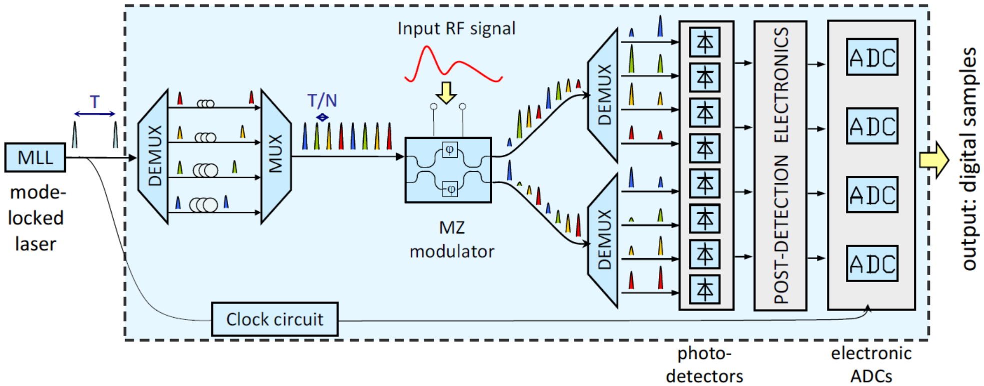
C. Bao *et al.*, *Opt. Lett.* **41**, 3876 (2016).

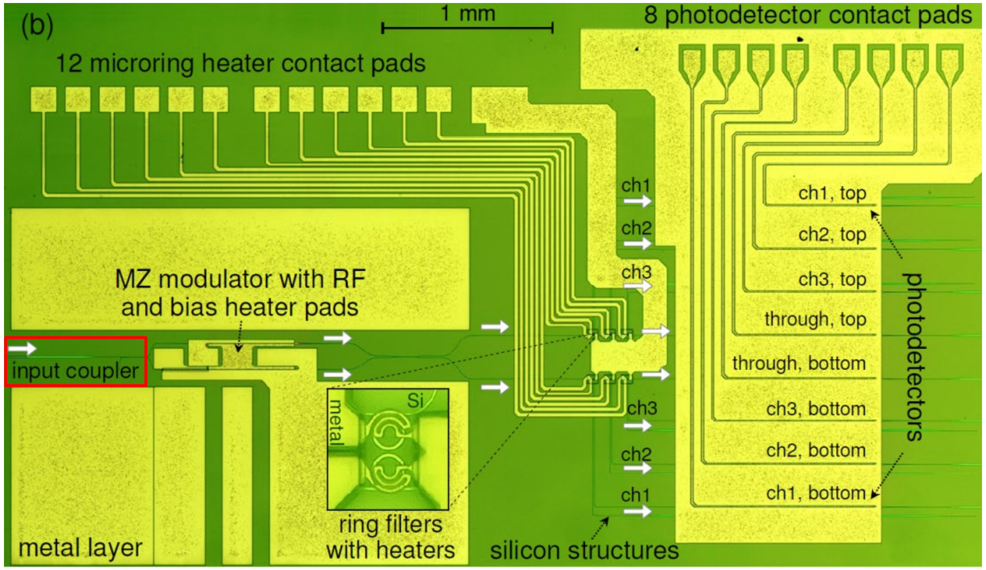


J. Pfeifle *et al.*, *Nat. Photon.* **8**, 375 (2014).

Photonic analog-digital converter





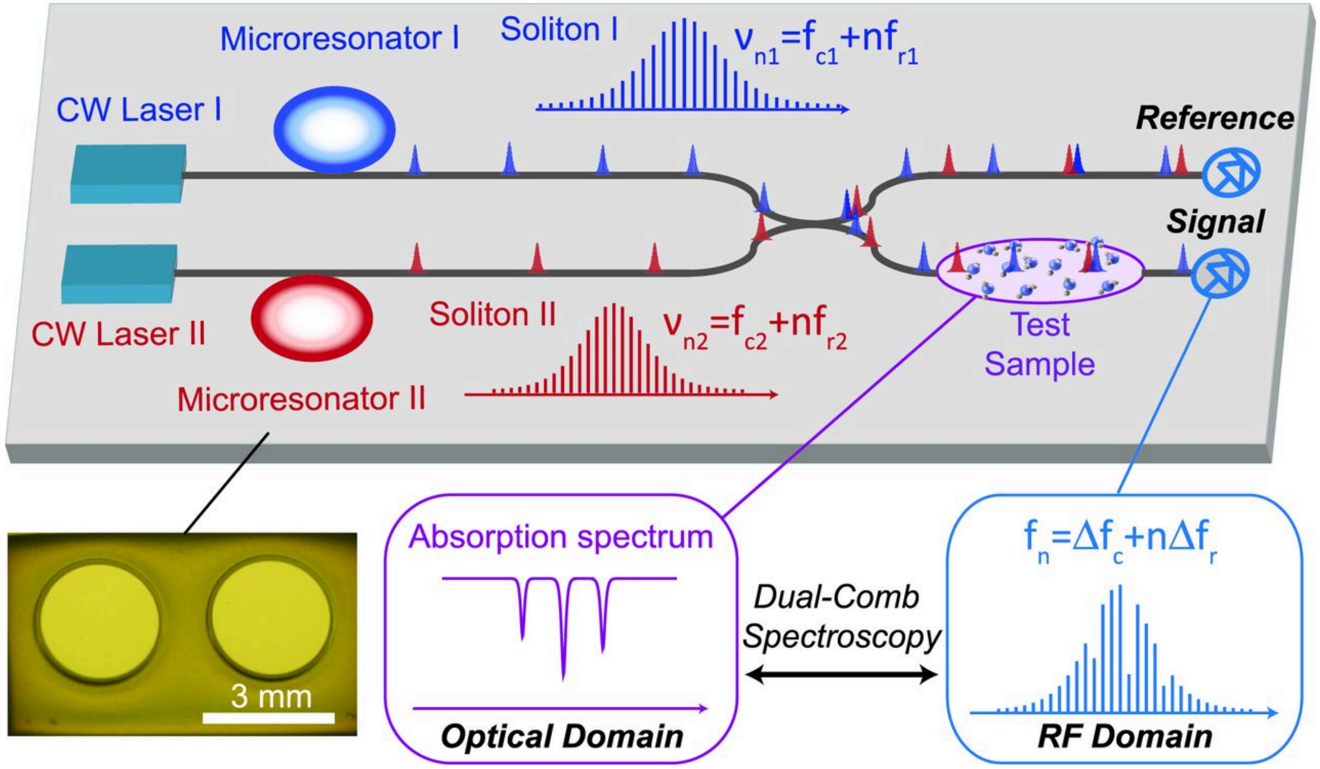


Sampling microwave signals directly in the optical domain with mode-locked lasers has shown promises to overcome the bottleneck of aperture jitter in the high-speed and high-resolution ADCs.

A. Khilo *et al.*, *Opt. Express* **20**, 4454 (2012).

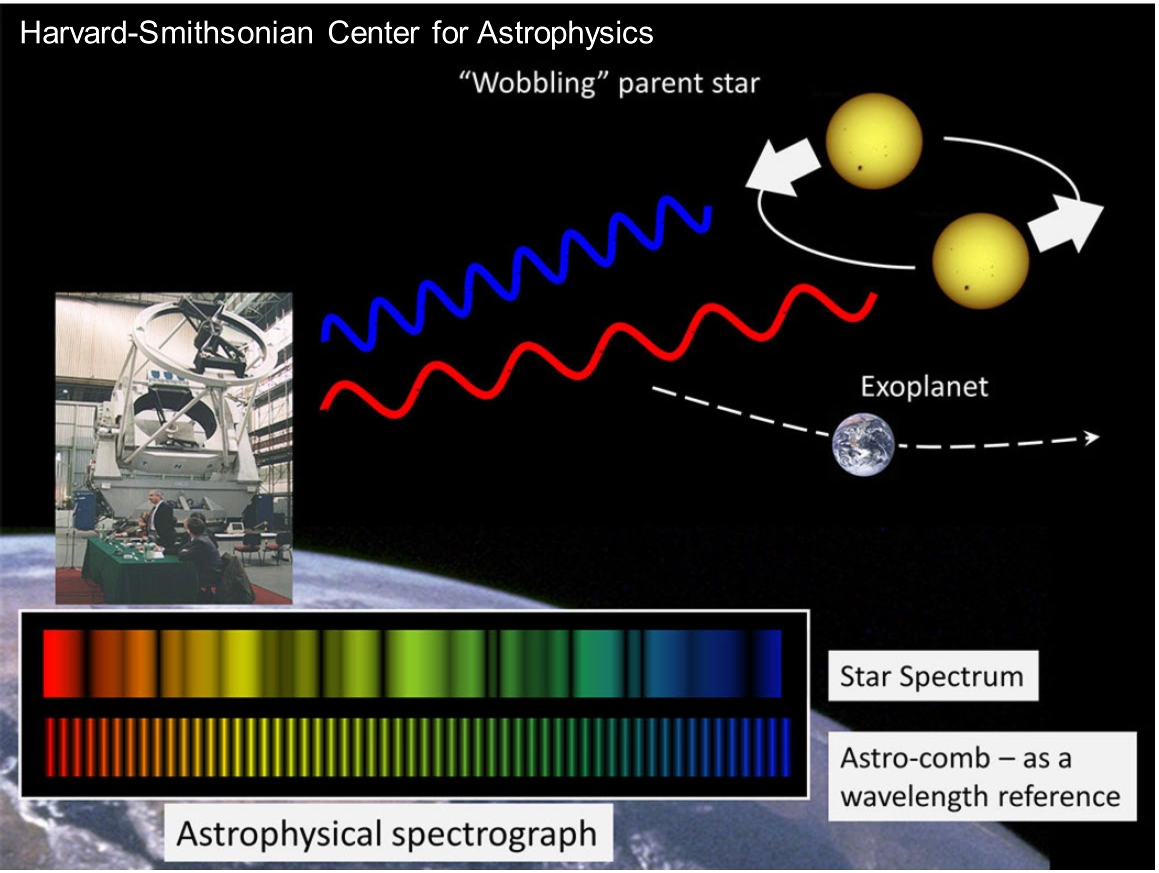
Chip-scale dual-comb spectroscopy

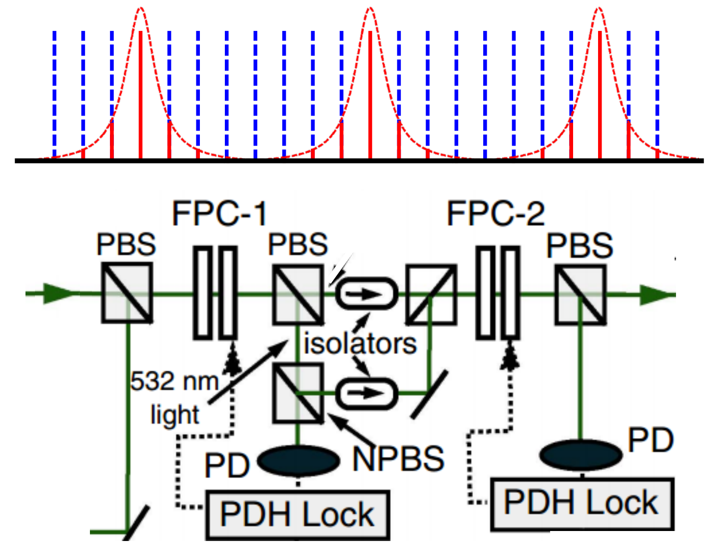
“The integration with other devices makes chip-scale Kerr frequency comb sources well suited for possible realization of a dual-comb spectroscopic system-on-a-chip.”



M.-G. Suh *et al.*, *Science* **354**, 600 (2016).

Astro-comb for earth-like exoplanet search





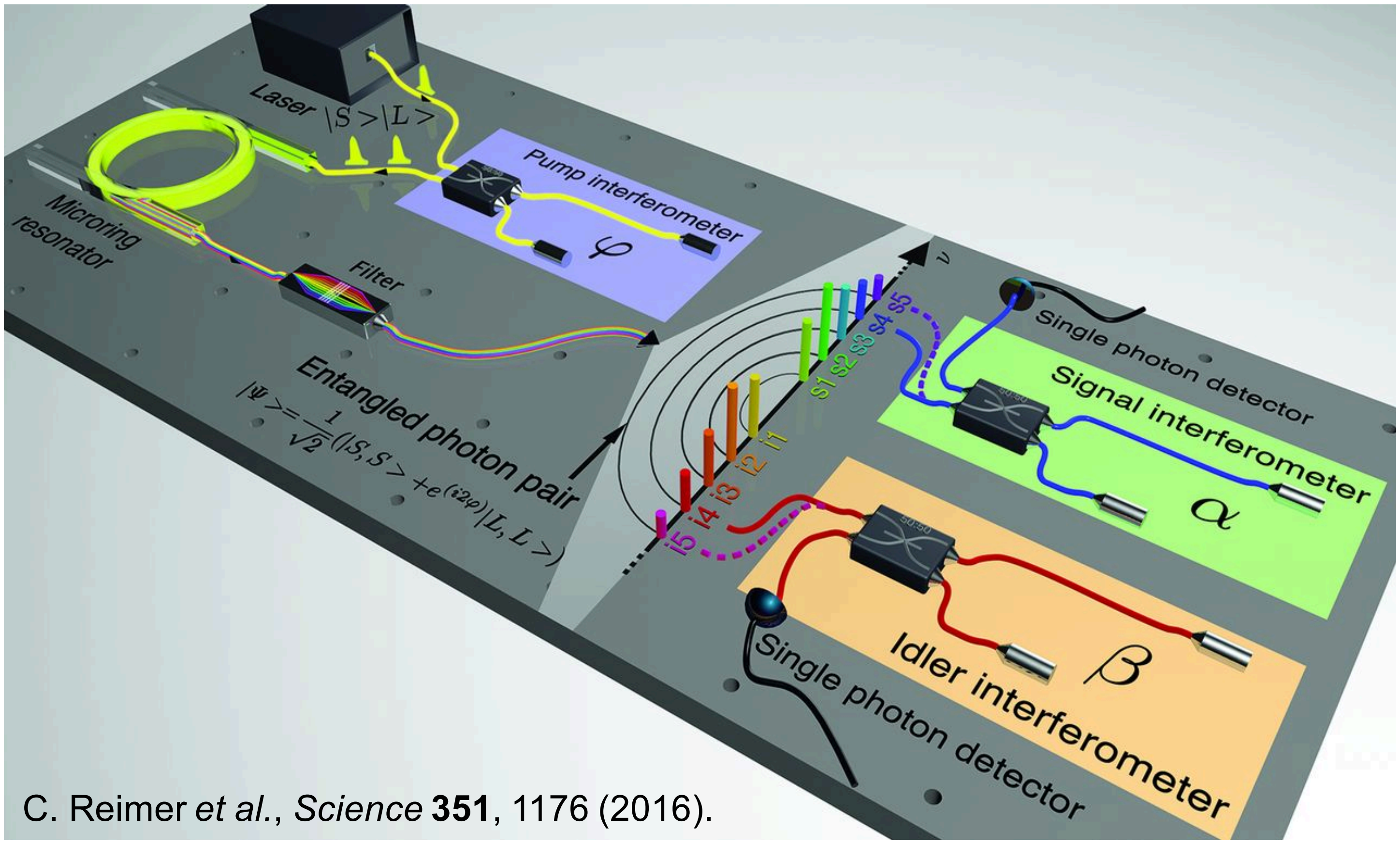
Finite side mode suppression and the instability of the external Fabry-Perot cavities are the limiting factor in precision.

C.-H. Li *et al*, *Nature* **452**, 610 (2008).
A. G. Glenday *et al.*, *Optica* **2**, 250 (2015).

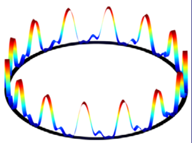
- Year-long precision radial velocity measurements will identify habitable exoplanets
- An ideal wavelength calibrator must have thousands of calibration lines, a bandwidth of >100 nm, a comb spacing of >10 GHz, an uniform comb line power of >100 nW, and a fractional uncertainty of $<3\times10^{-11}$.

Optical quantum information processing

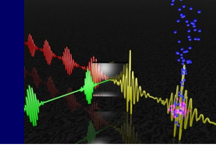
“The exploitation of integrated Kerr frequency combs, with their ability to generate multiple, customizable, and complex quantum states, can provide a scalable, practical, and compact platform for quantum technologies.”

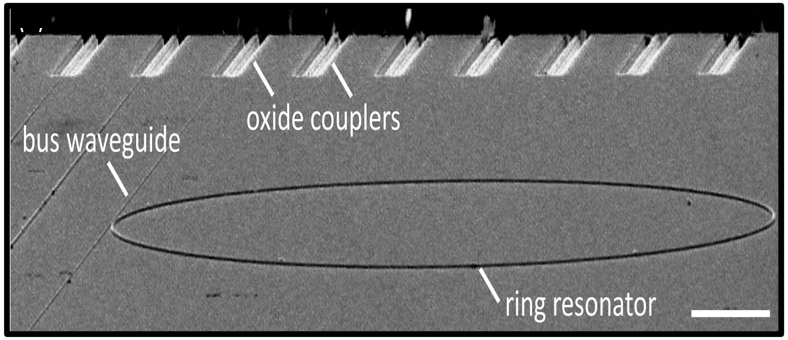


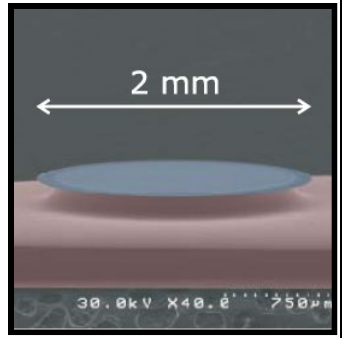
C. Reimer *et al.*, *Science* **351**, 1176 (2016).

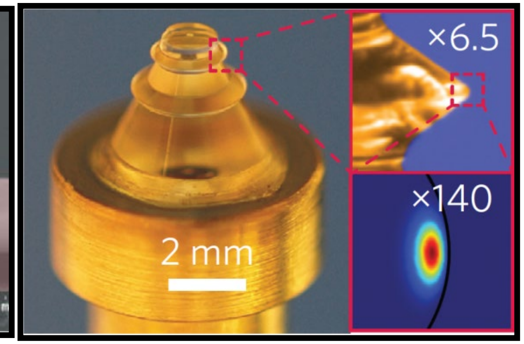


I. Microresonator-based ultrafast light source







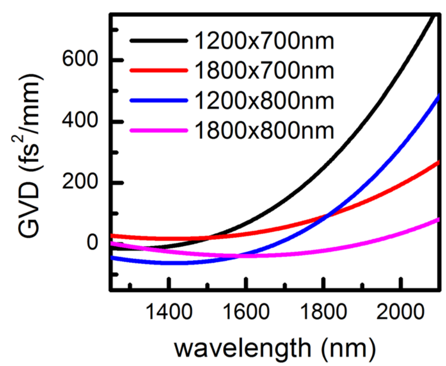


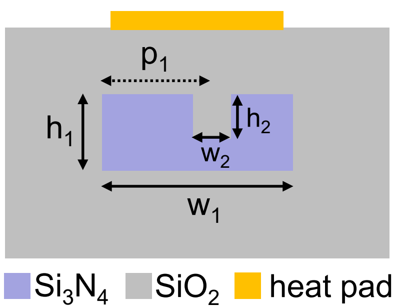
Columbia – silicon nitride
EPFL – silicon nitride
Purdue – silicon nitride
<u>UCLA – silicon nitride</u>
RMIT/INRS – Hydex
Harvard – diamond
Yale – aluminum nitride
DTU – aluminum gallium arsenide

Caltech – silica
EPFL – CaF_2/MgF_2
JPL – CaF_2/MgF_2
OEwaves – CaF_2/MgF_2
NIST – fused quartz

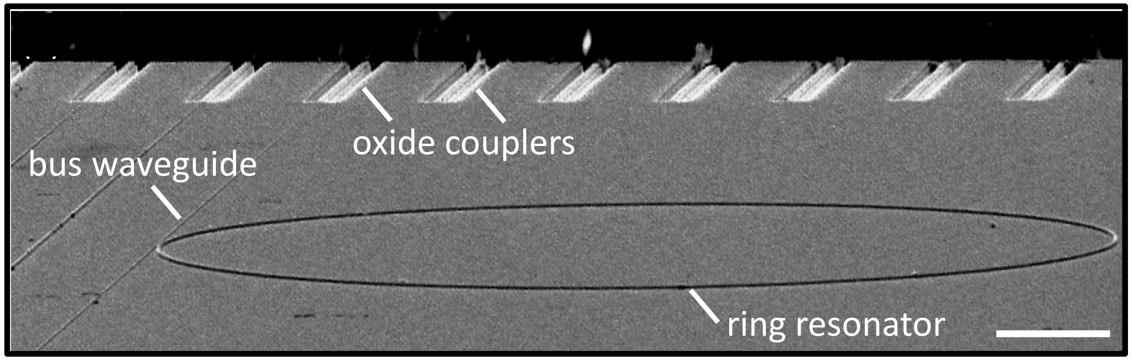
planar ring cavities are attractive

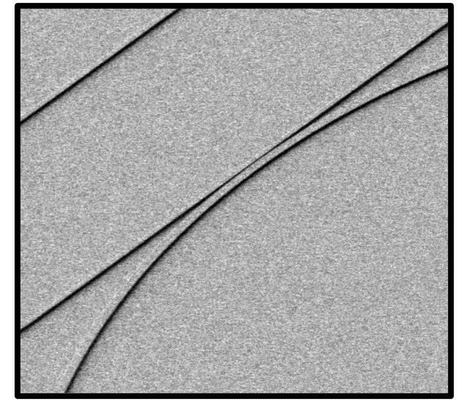
1. potential of electronic-photonic integration
2. flexibility of tailoring cavity dispersion

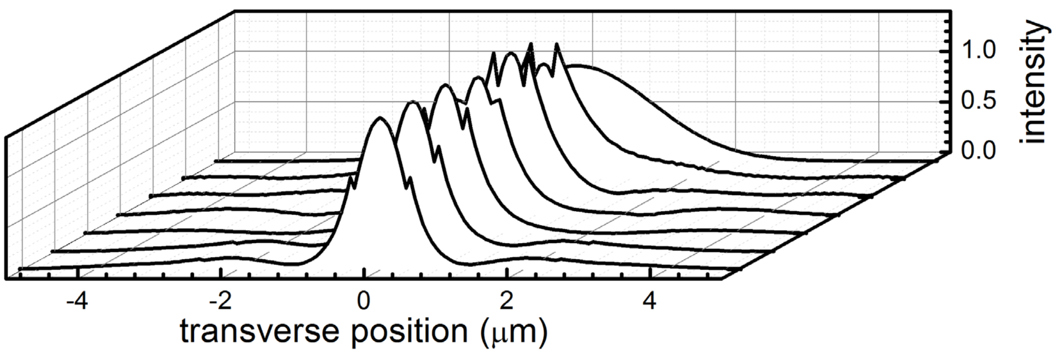


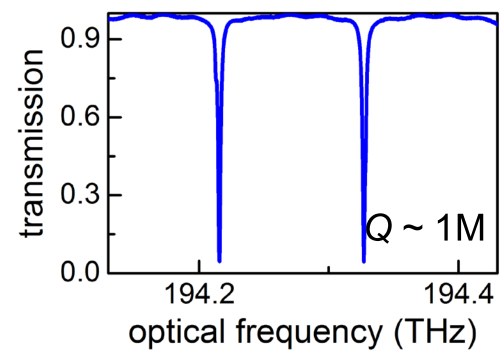


Baseline process control: Si_3N_4 μresonators









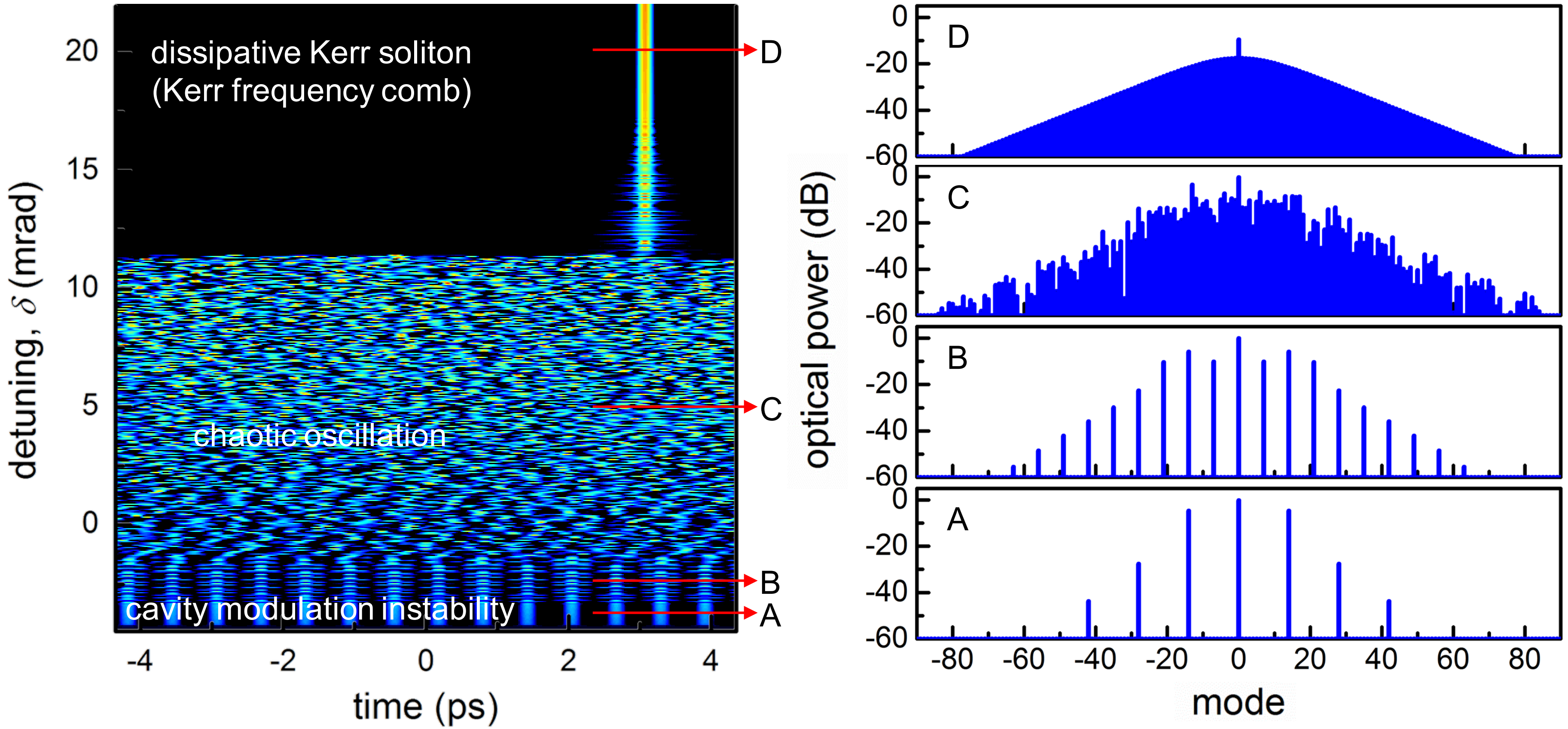
- fiber-to-fiber coupling loss is 5 dB
- sidewall angle is 88 degree
- smallest feature is 200 nm
- propagation loss is 0.2 dB/cm

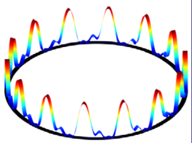
fabricated in the Institute of Microelectronics Singapore

Nonlinear dynamics in microresonators

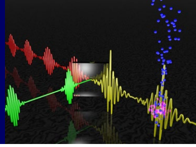
$$T_R \frac{\partial}{\partial T} A = -\left(\frac{\alpha}{2} + \frac{T}{2} + j\delta\right) A + j \frac{\beta_{2\Sigma}}{2} \frac{\partial^2}{\partial t^2} A - j\gamma_\Sigma |A|^2 A + \sqrt{T} A_{in}$$

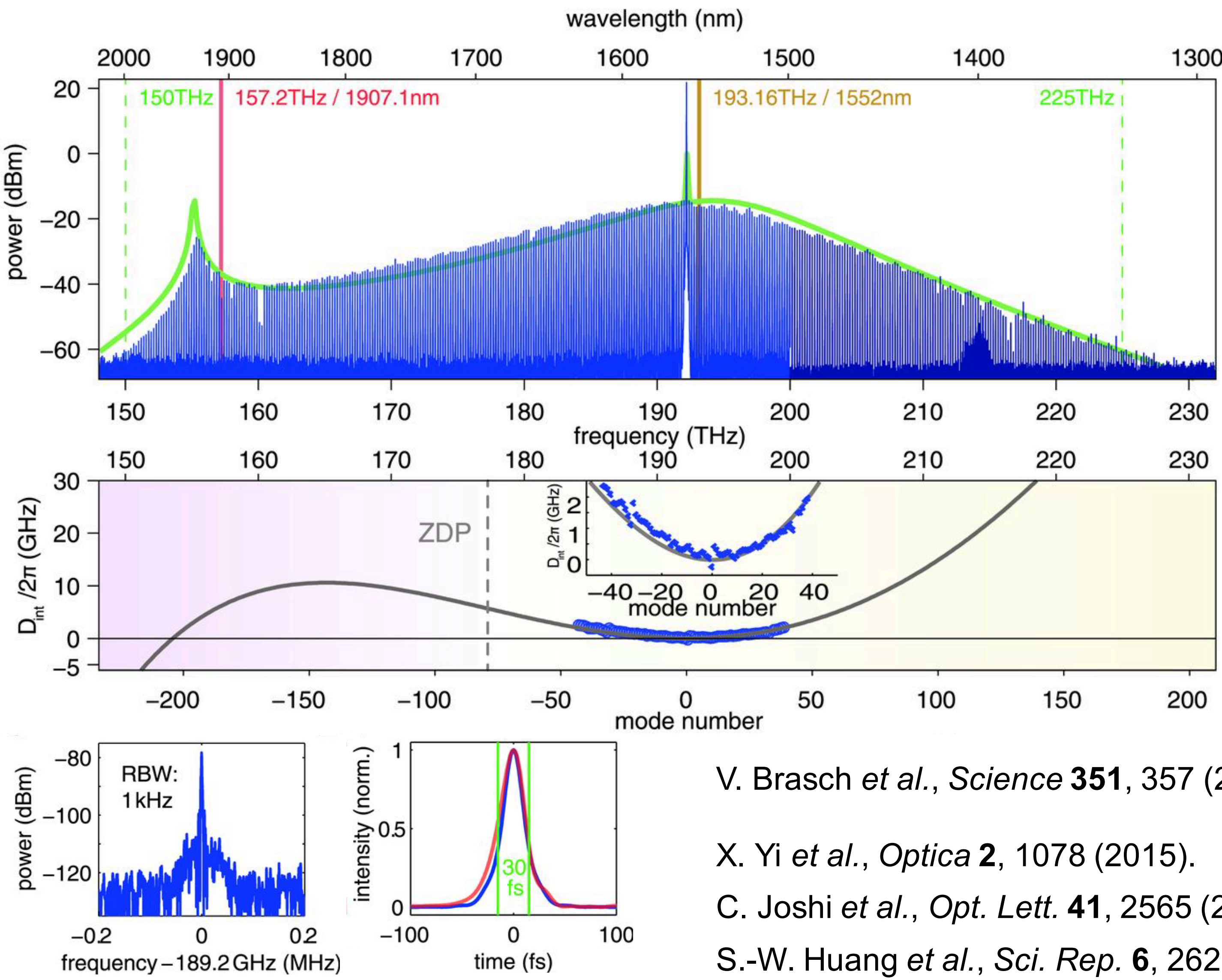
detuning GVD SPM pump





Pulses in anomalous GVD μresonators



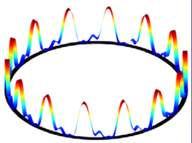


V. Brasch *et al.*, *Science* **351**, 357 (2016).

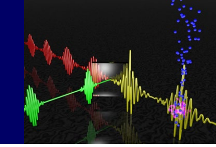
X. Yi *et al.*, *Optica* **2**, 1078 (2015).

C. Joshi *et al.*, *Opt. Lett.* **41**, 2565 (2016).

S.-W. Huang *et al.*, *Sci. Rep.* **6**, 26255 (2016).



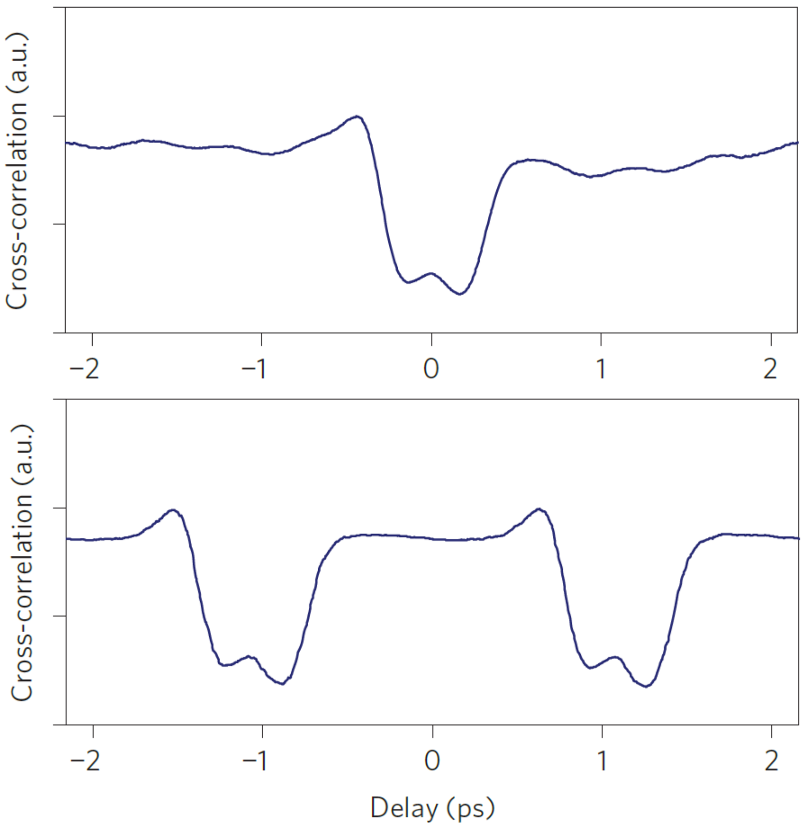
Pulses in normal GVD μresonators

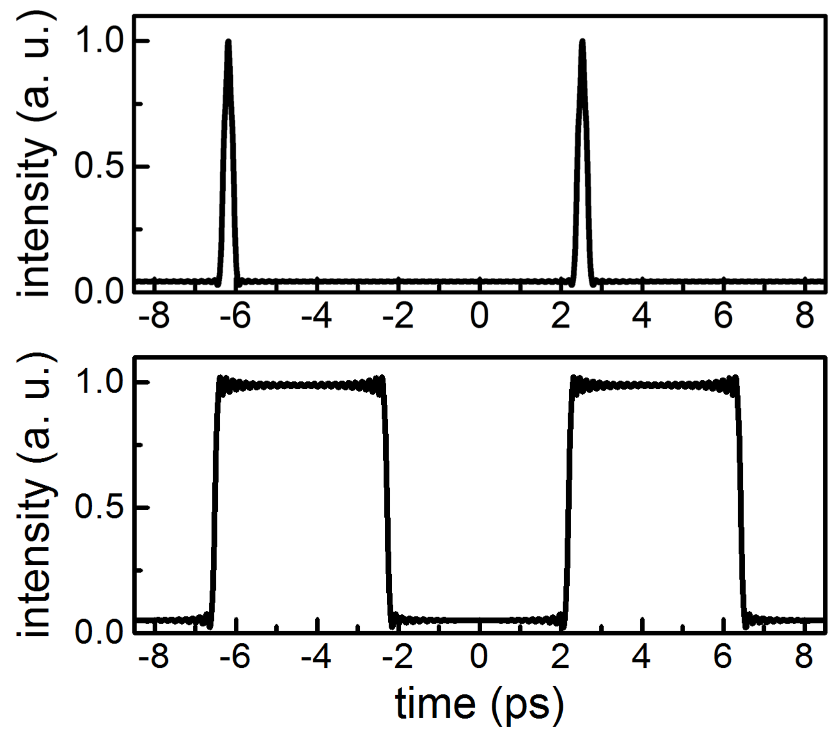


dark pulses

$$T_R \frac{\partial}{\partial T} A = -\left(\frac{\alpha}{2} + \frac{T}{2} + j\delta\right) A + \sqrt{T} A_{in} + j\left(\frac{\beta_{2\Sigma}}{2} - j\frac{T}{\Omega_f^2}\right)\frac{\partial^2}{\partial t^2} A - j\gamma_\Sigma |A|^2 A$$

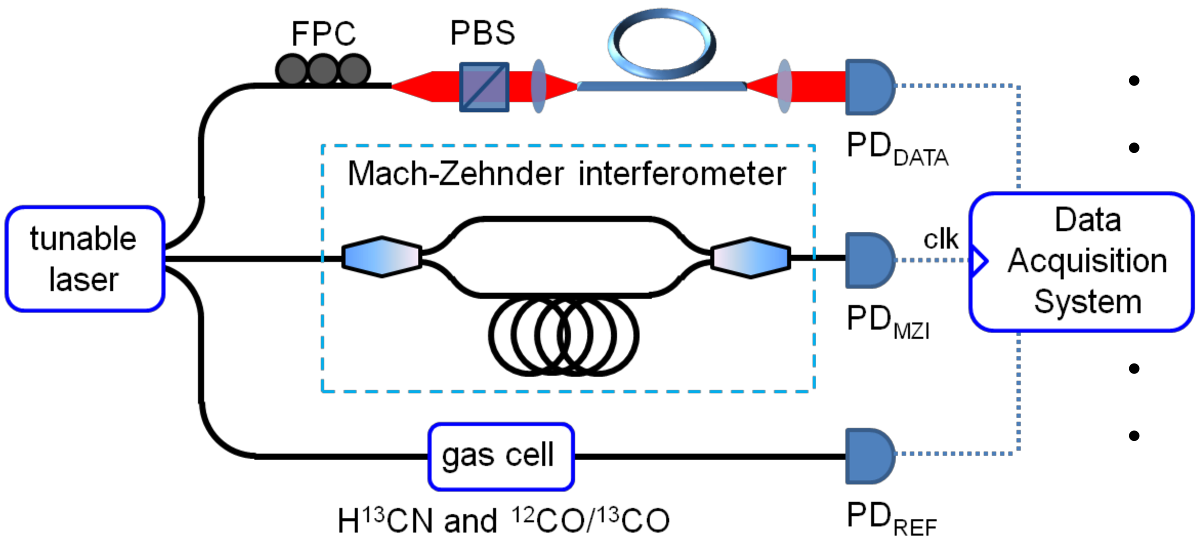
intracavity filtering



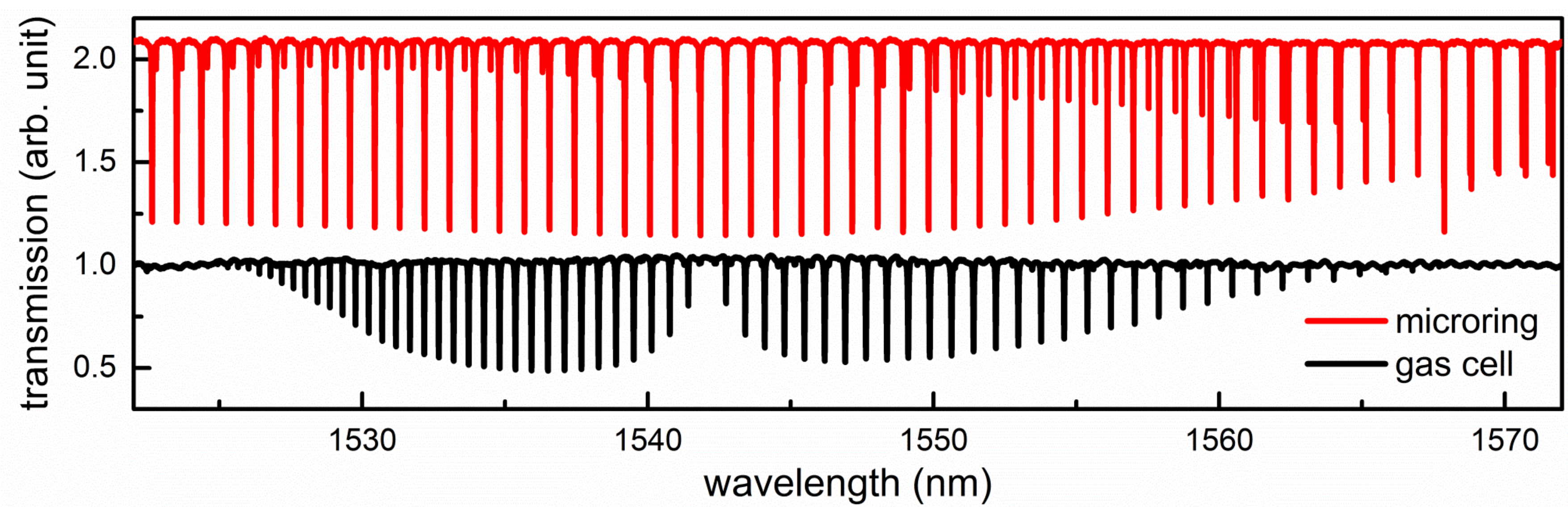


X. Xue *et al.*, *Nat. Photon.* **9**, 594 (2015).

Coherent swept wavelength interferometer

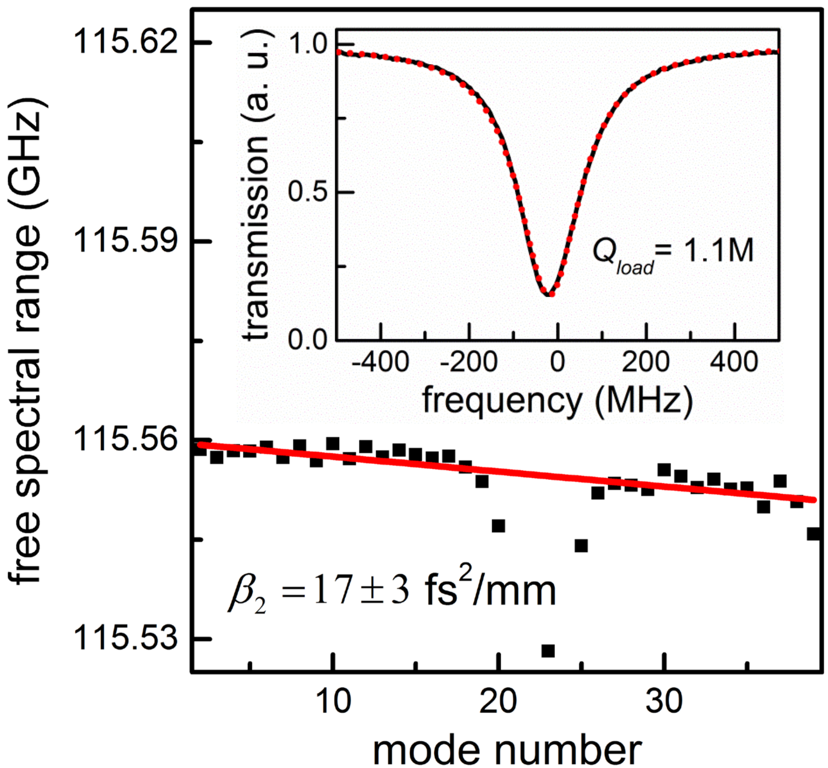


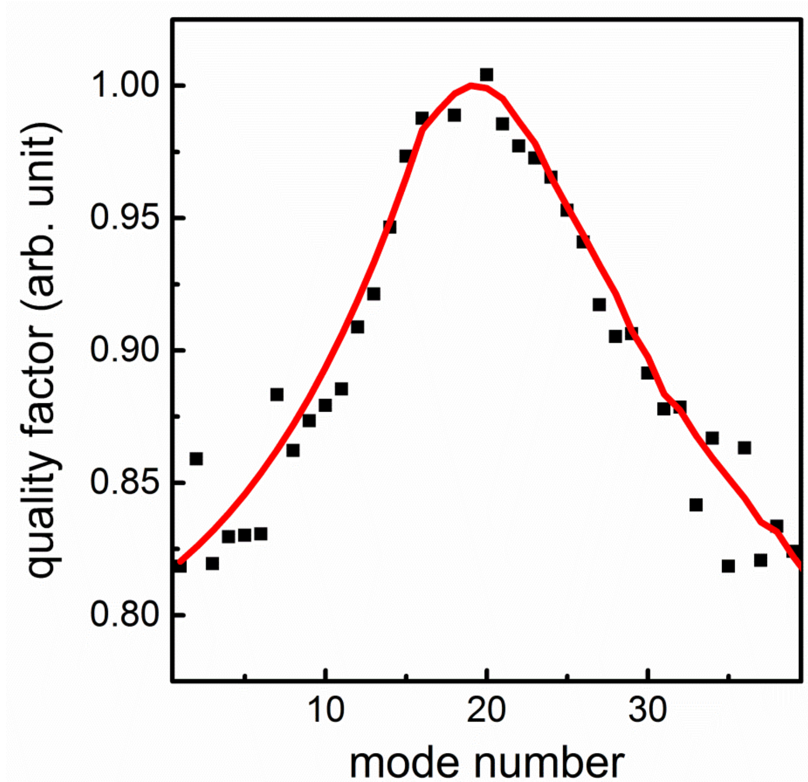
- scan speed: >40 nm/s
- MZI clock: 5 MHz sampling
- synchronous gas cell measurement
- active temperature stabilization



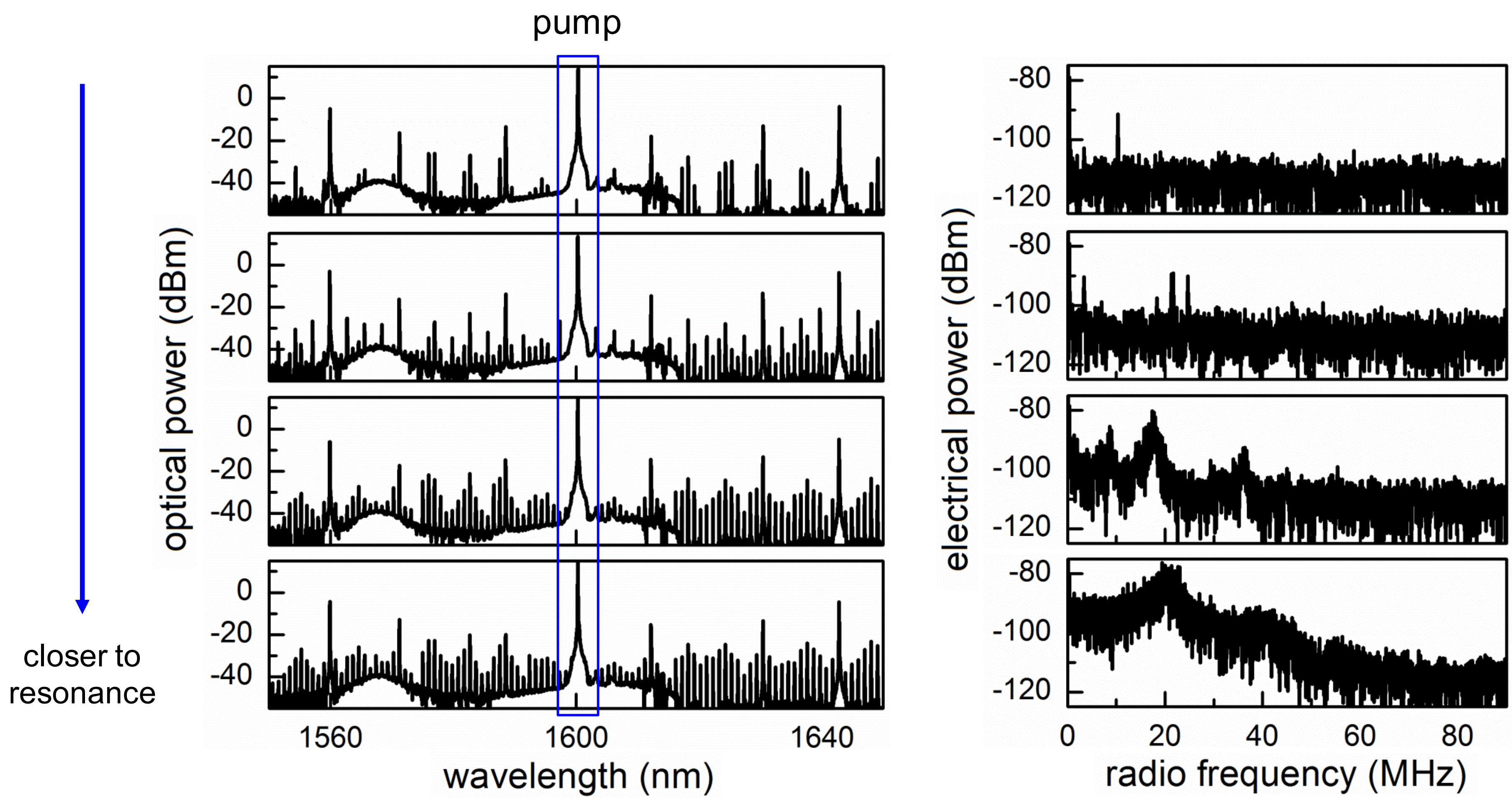
Measurements of GVD and intracavity filter

Each resonance is fitted with a Lorentzian lineshape to find the resonance frequency and the quality factor. The GVD is then determined by analyzing the dependence of the free spectral range on the mode number.

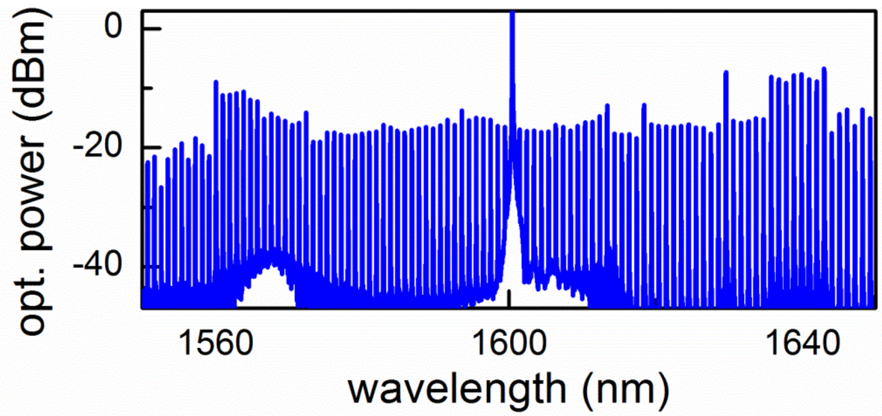




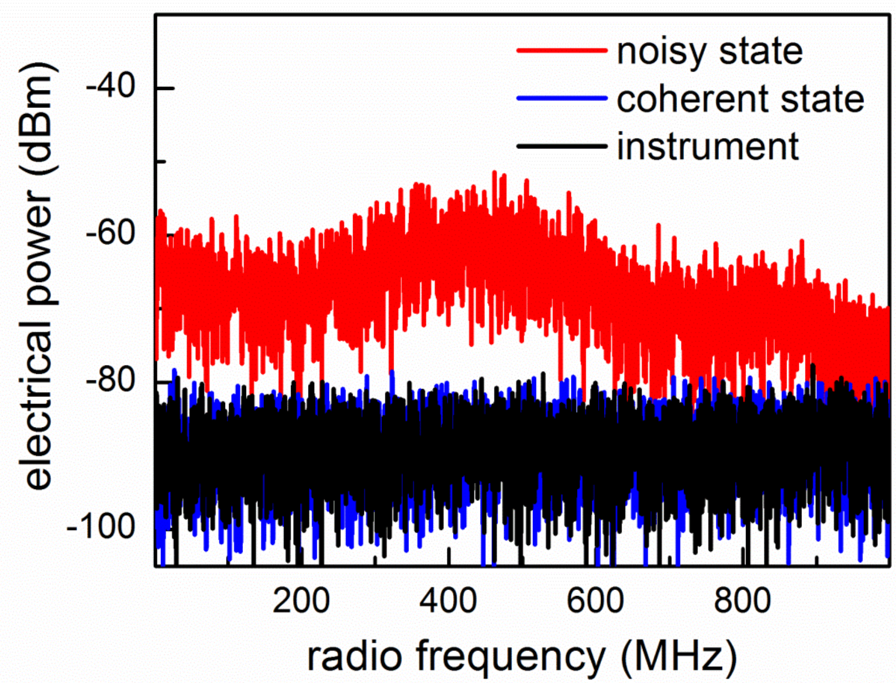
State evolution in microresonator

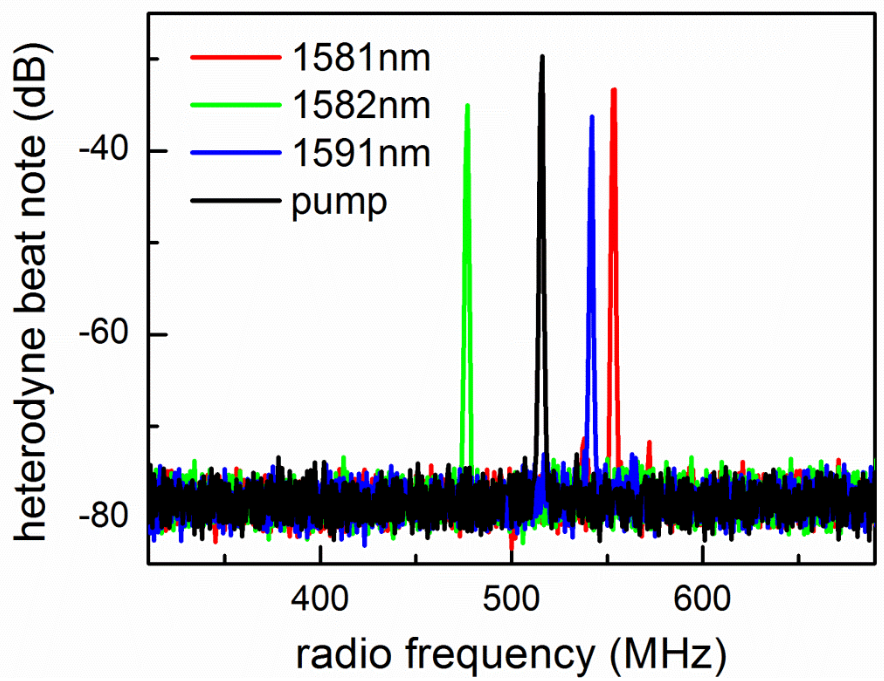


Establishment of coherence

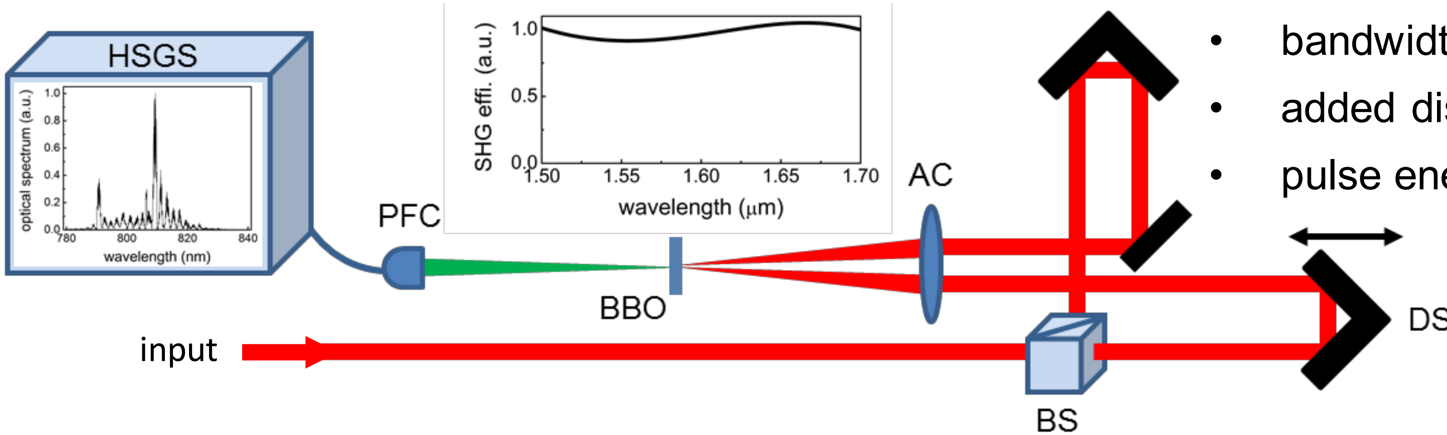


- A stepwise change of resonance detuning or pump power drives the microresonator into the Kerr frequency comb state.
- All heterodyne beat notes exhibit the same linewidth of 800 kHz, limited by the mutual coherence of the pump and the reference.

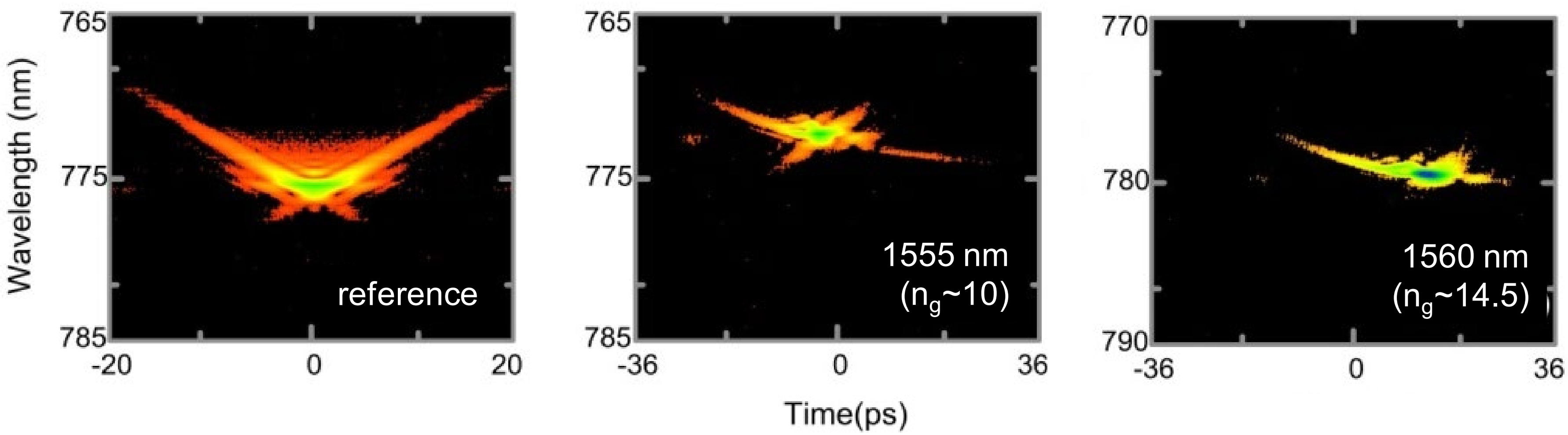




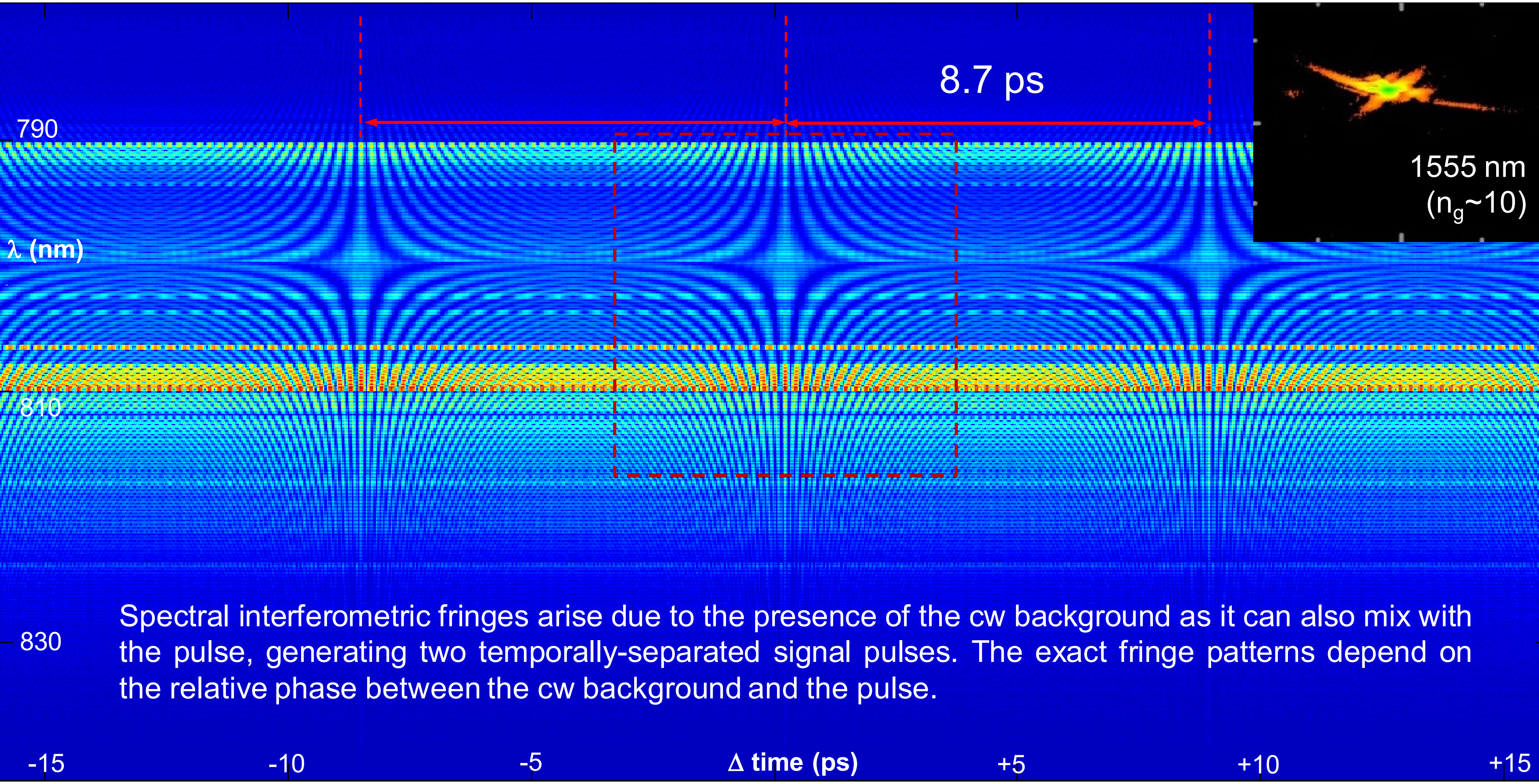
Frequency resolved optical gating (FROG)



- bandwidth: >200 nm
- added dispersion: -50 fs^2
- pulse energy: <100 aJ (1 sec)



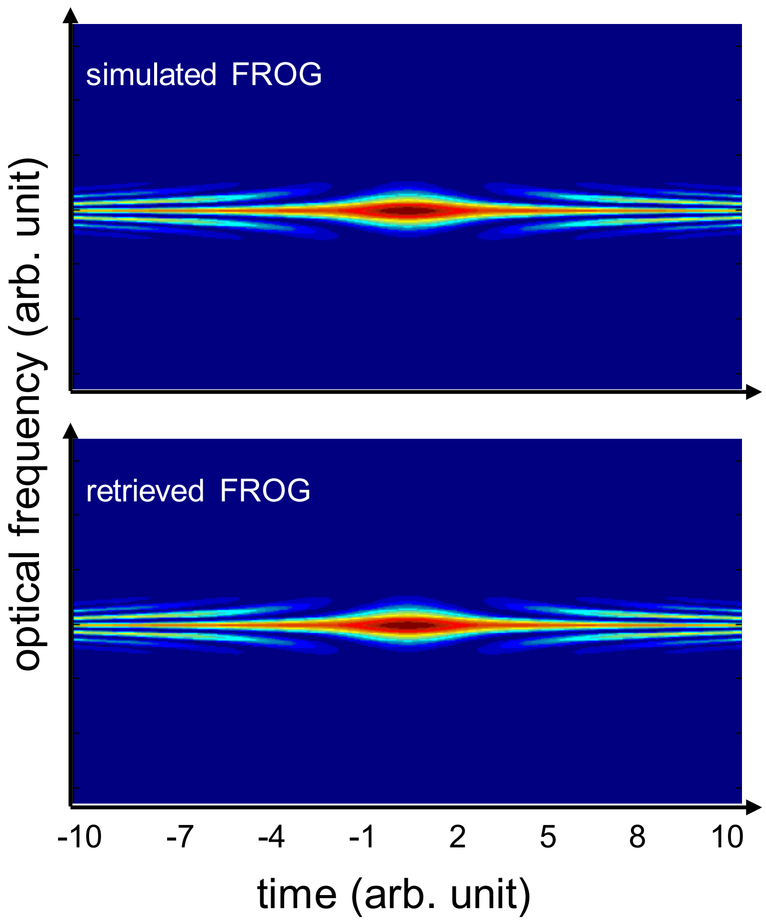
FROG spectrogram

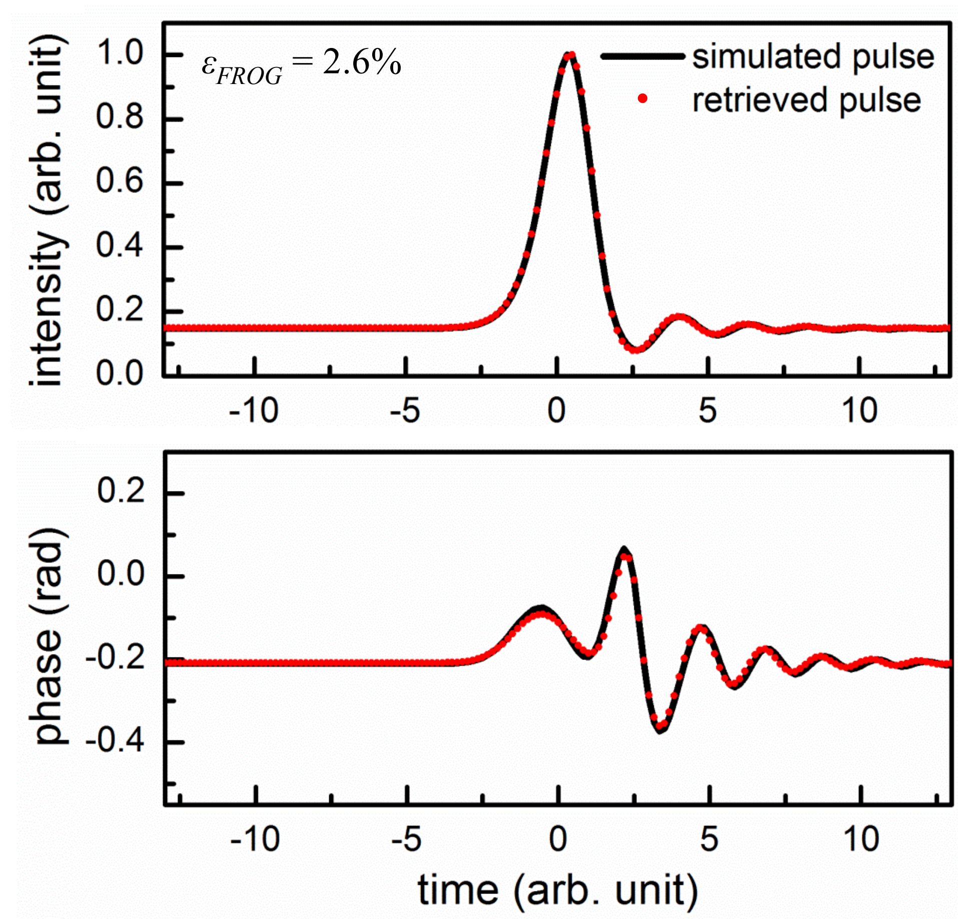


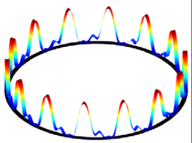
Spectral interferometric fringes arise due to the presence of the cw background as it can also mix with the pulse, generating two temporally-separated signal pulses. The exact fringe patterns depend on the relative phase between the cw background and the pulse.

Genetic algorithm for phase retrieval

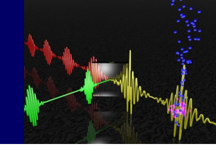
Genetic algorithm is a global search method based on ideas taken from evolution and is less susceptible to becoming trapped by local extrema in the search space.

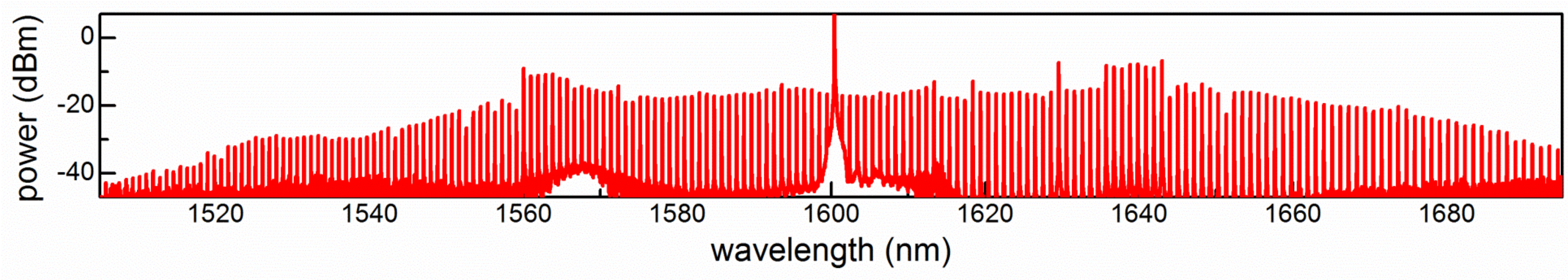


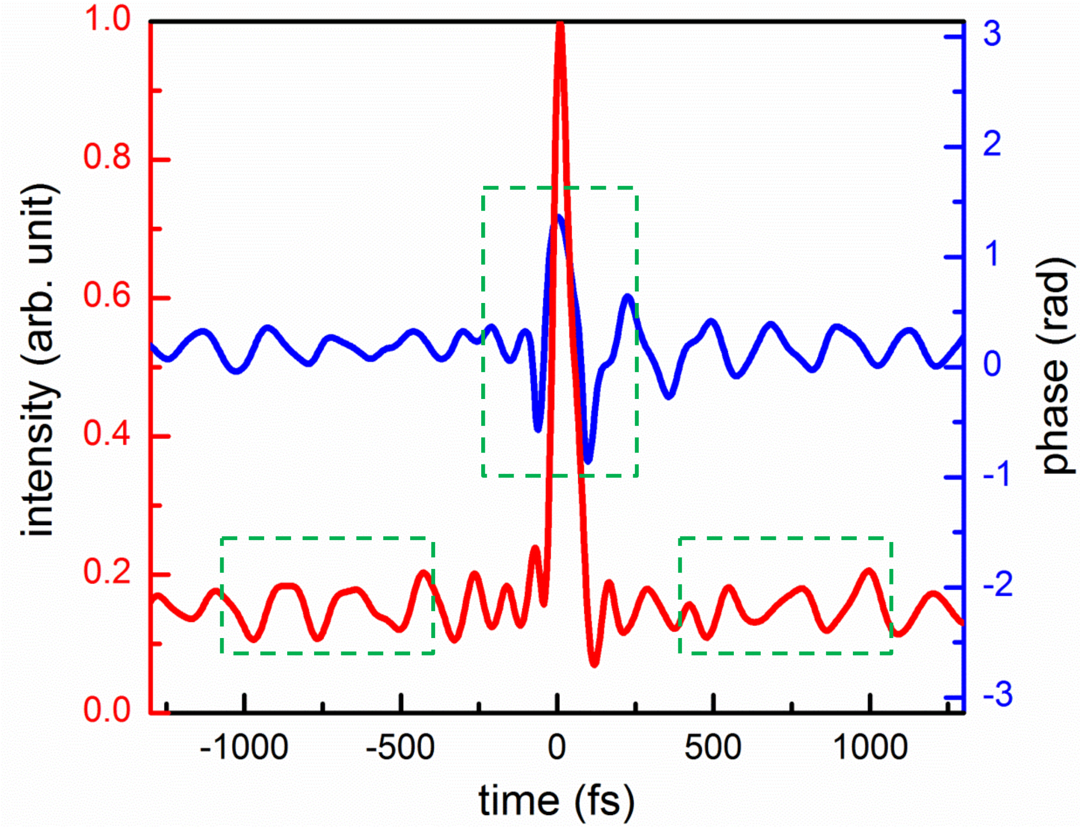




FROG retrieved pulse structure





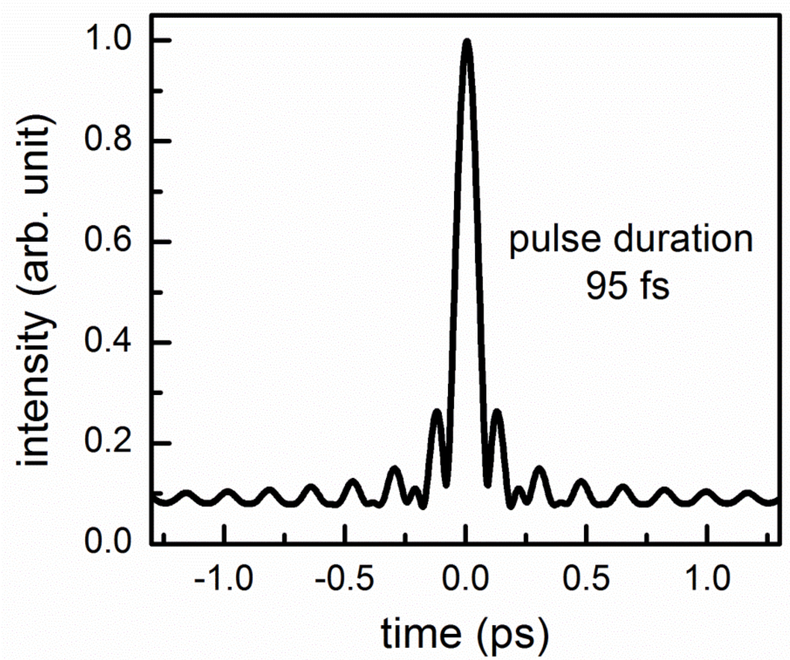


pulse duration is 74 fs, positively chirped from the ideal pulse duration of 55 fs

1.3 rad phase contrast is observed within the pulse

continuous-wave background is essential for the existence of stable pulses

Bright pulse and analytic solution



pulse peak power is much higher than cw background

$$|A_{p0}|^2/|A_c|^2 \gg 1$$

pulse energy is much lower than cw energy

$$\int_0^{T_R} |A_c|^2 dt \Big/ \int_0^{T_R} |A_p|^2 dt \gg 1$$

time bandwidth product is much larger than unity

$$q^2 \gg \Omega_f^2 \tau^2 \gg 1$$

ansatz:

$$A(T,t) = A_c + A_p(T,t)$$

$$A_p(T,t) = A_{p0}\left[exp\left(\frac{t}{\sqrt{2}\tau}\right)^2\right]^{-1-iq} e^{i\varphi_p}$$

solution:

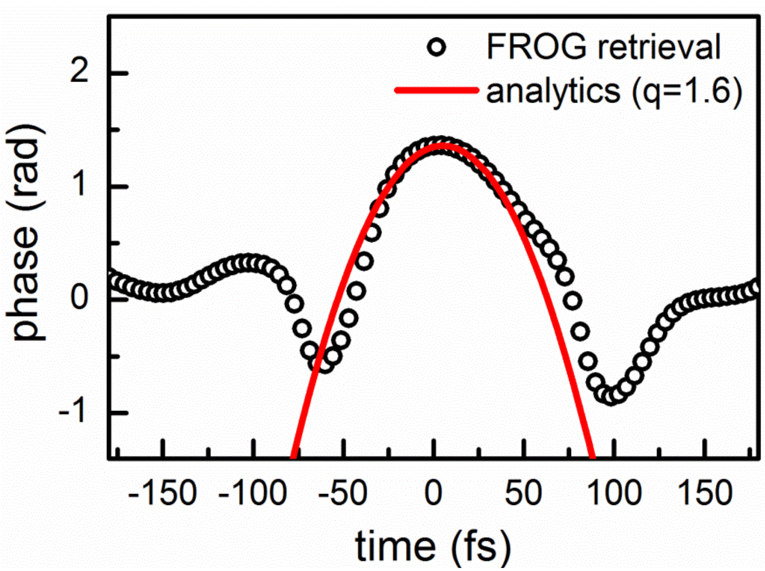
$$q \cong \frac{4\beta_{2\Sigma}\Omega_f^2}{3T}$$ chirp

$$\tau \cong \frac{1.5\beta_{2\Sigma}^{\frac{3}{2}}\Omega_f^2}{T\sqrt{\delta}}$$ pulse duration

Matching with the FROG retrieval

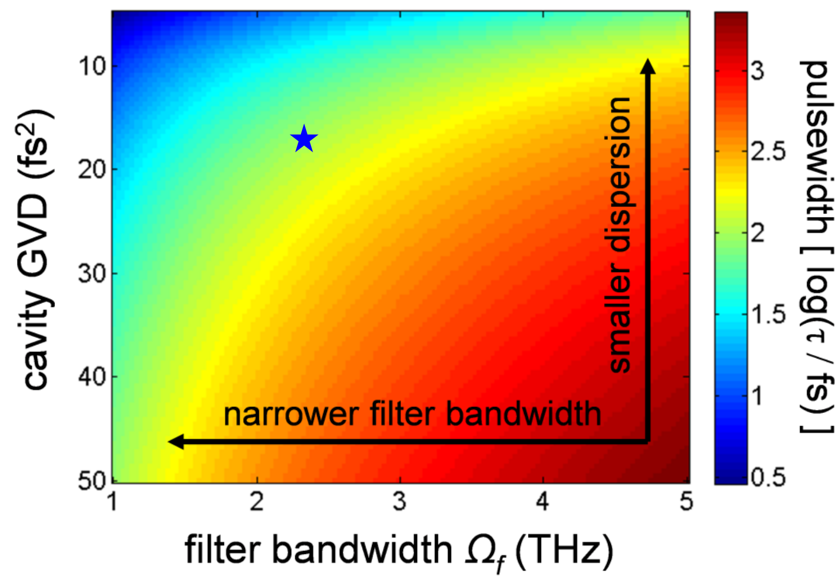
Analytically calculated chirp agrees well with the FROG retrieval.

$$q \cong \frac{4\beta_{2\Sigma}\Omega_f^2}{3T}$$

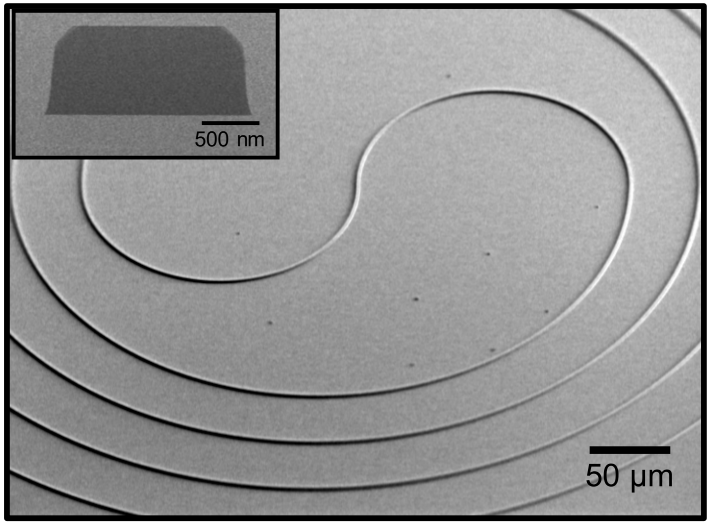


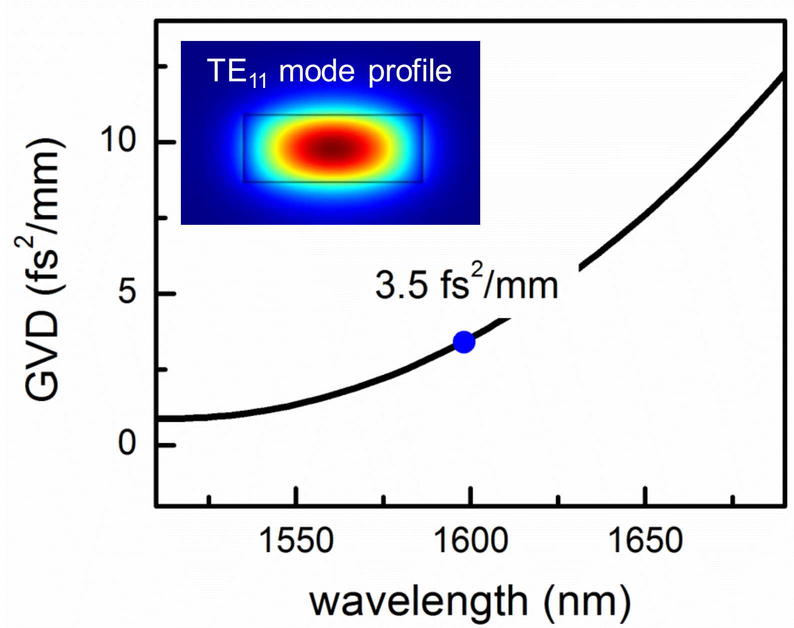
A narrower filter bandwidth and smaller GVD are beneficial for short pulses.

$$\tau \cong \frac{1.5\beta_{2\Sigma}^{\frac{3}{2}}\Omega_f^2}{T\sqrt{\delta}}$$



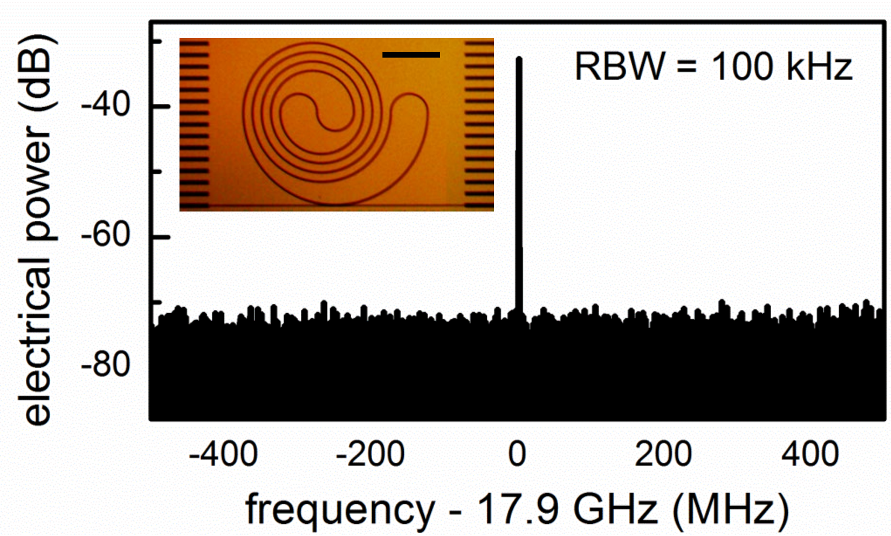
II. Low noise broadband microcomb

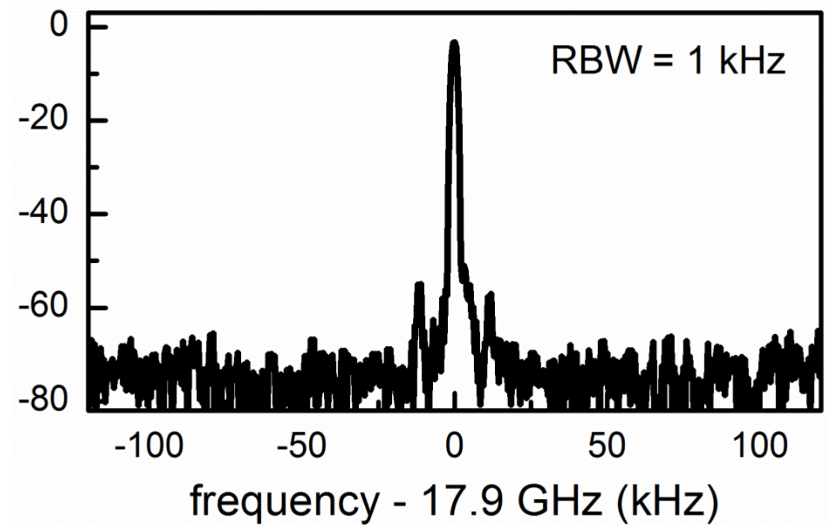


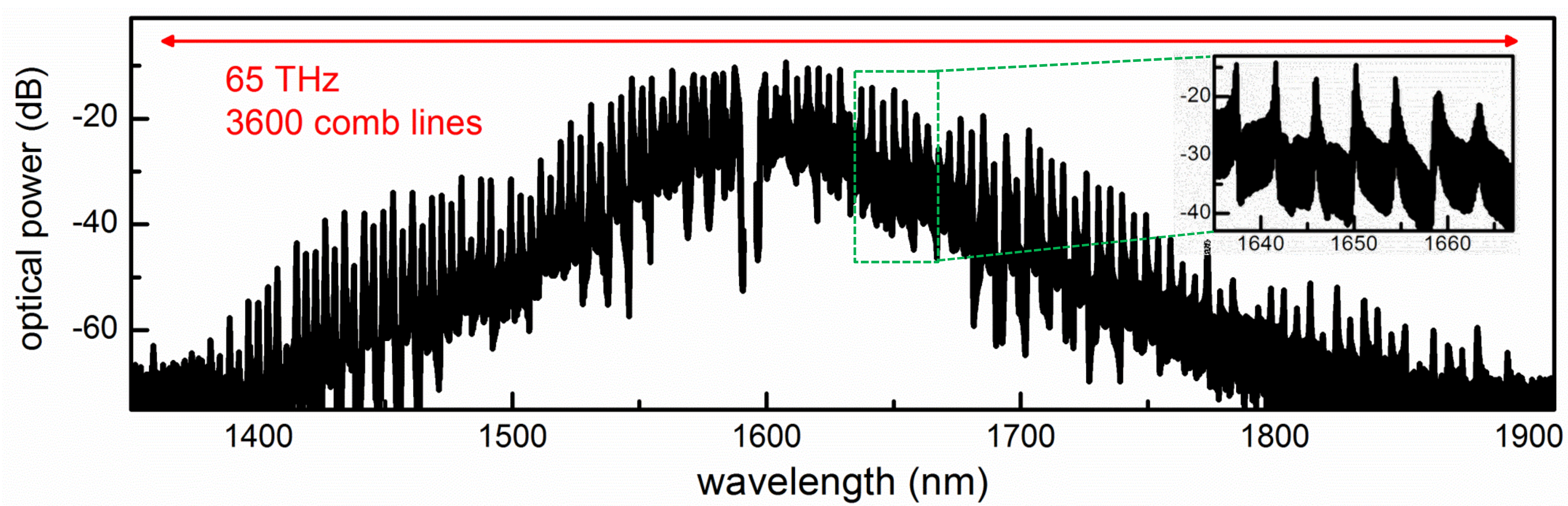


1. Microresonator-based ultrafast light source delivering 74 femtosecond pulse train
   - Huang *et al.*, *Phys. Rev. Lett.* **114**, 053901 (2015).
2. Low noise broadband microcomb containing 3,600 coherent frequency teeth
   - Huang *et al.*, *Sci. Rep.* **5**, 13355 (2015).
3. High bandwidth comb stabilization achieving a fractional uncertainty of 2.7×10^{-16}
   - Huang *et al.*, *Sci. Adv.* **2**, e1501489 (2016).
4. Microresonator stabilized diode laser at the thermodynamical limit of 1.7×10^{-13}
   - Lim *et al.*, *Opt. Lett.* **41**, 3706 (2016).

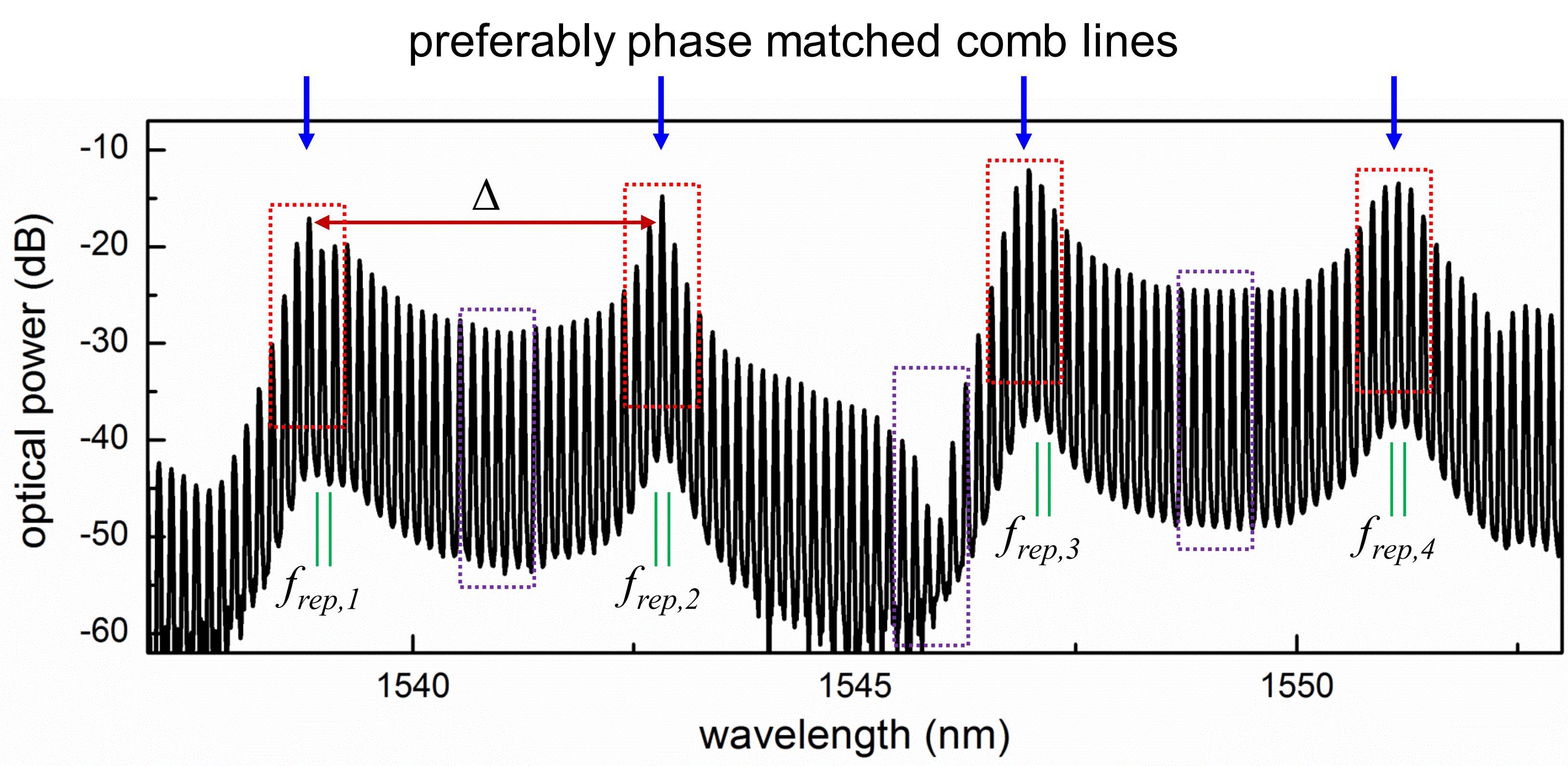
Half-octave-spanning coherent comb spectrum







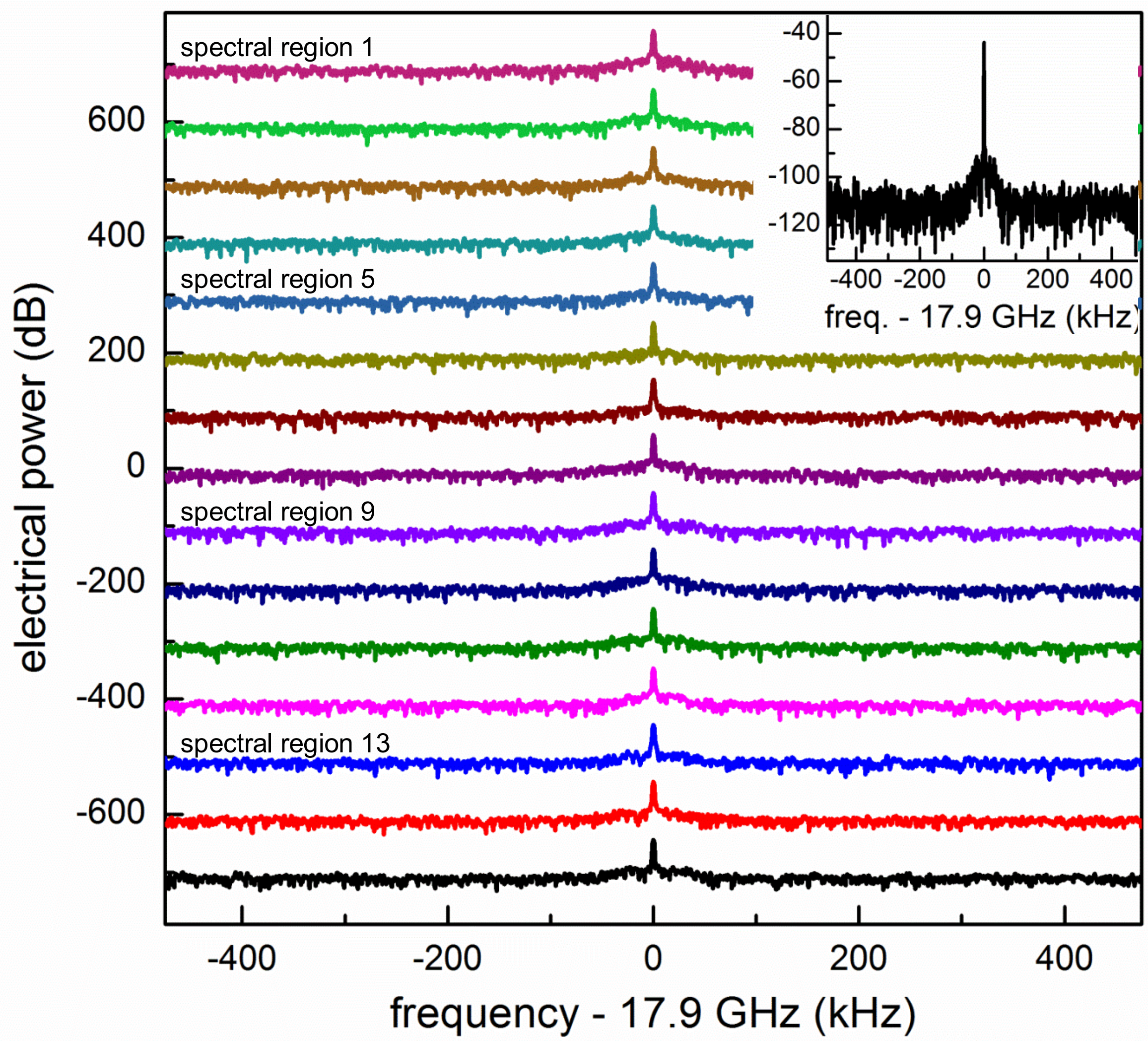
Coherence between different comb families

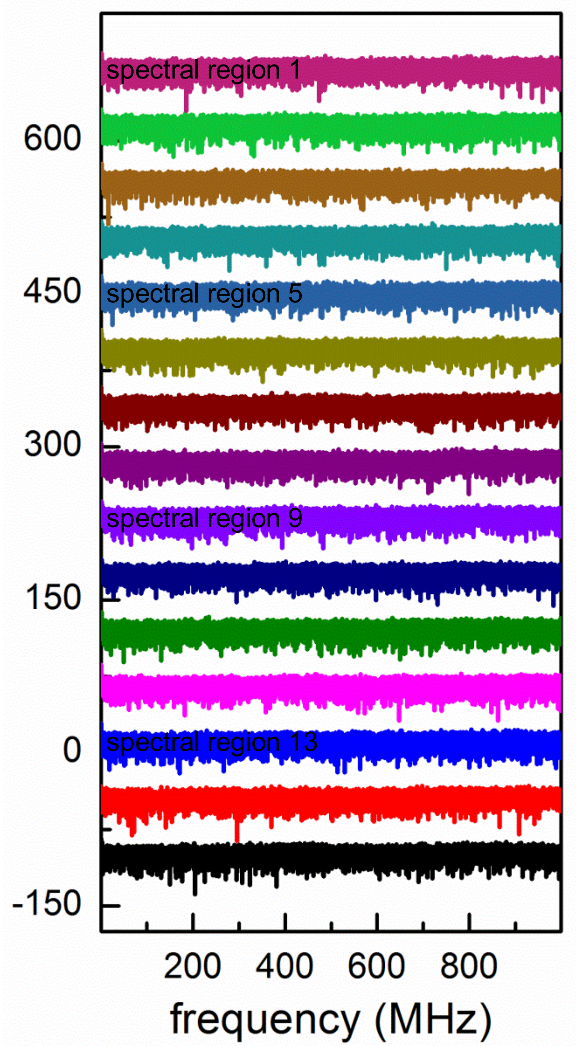


To use the constitutive equation $f_n = n \cdot f_{rep} + f_{ceo}$

, comb spacing needs to be equal across the full spectrum $f_{rep,1} = f_{rep,2} = \ldots = f_{rep}$
, and Δ needs to be commensurate with the comb spacing $\Delta = N f_{rep}$

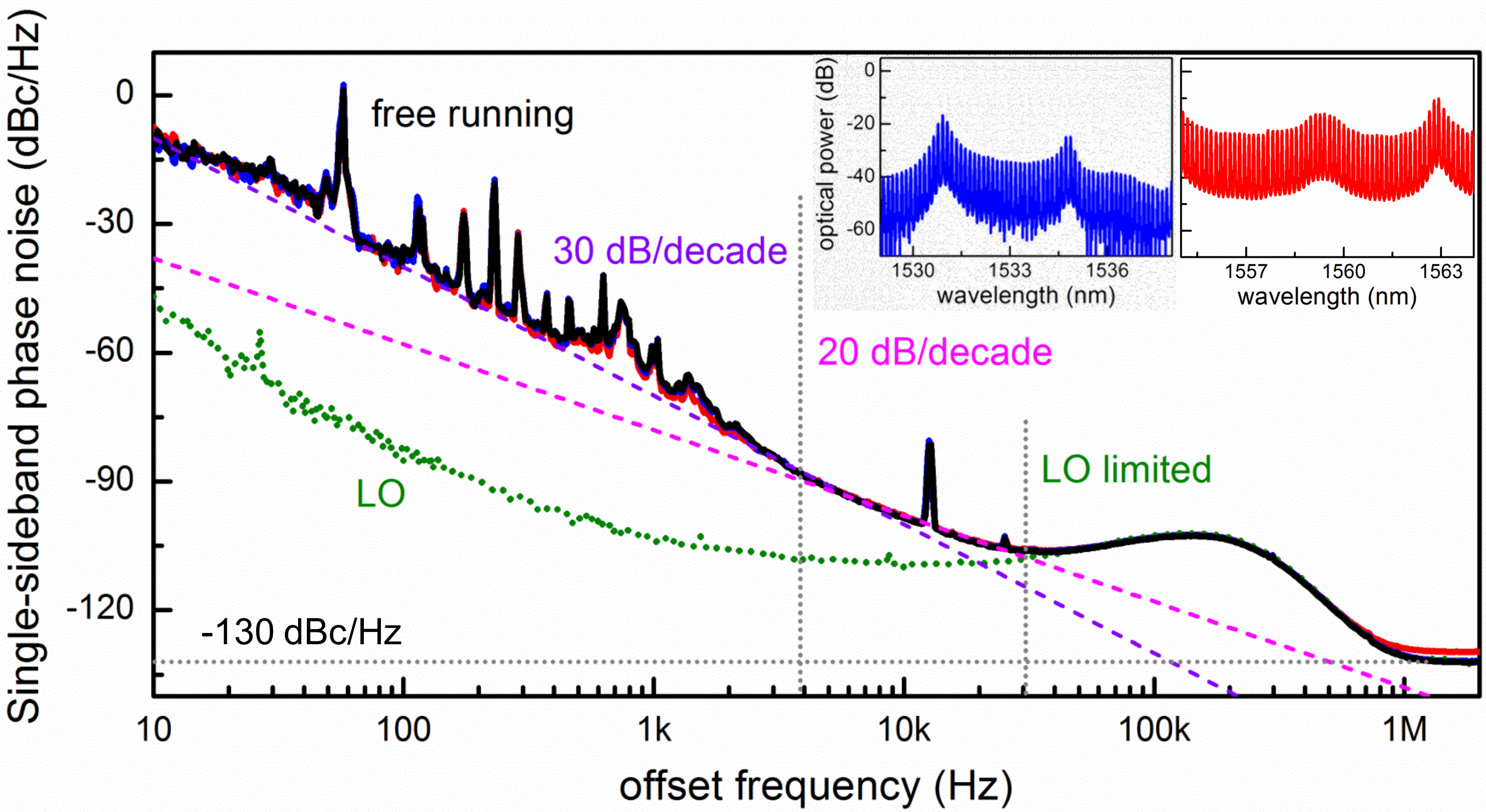
Verification of continuously-equidistant comb





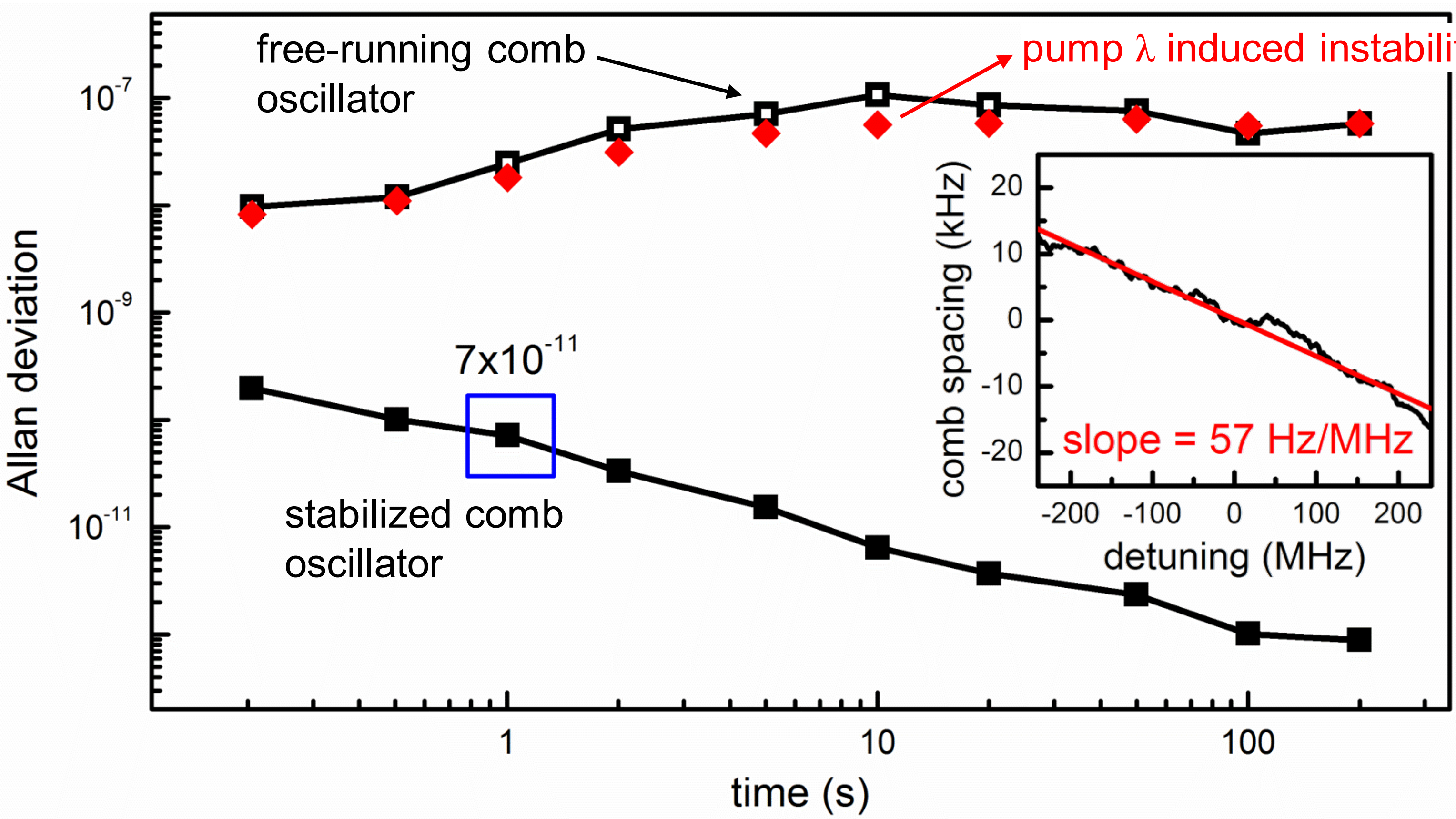
Phase noise analysis of the μcomb oscillator

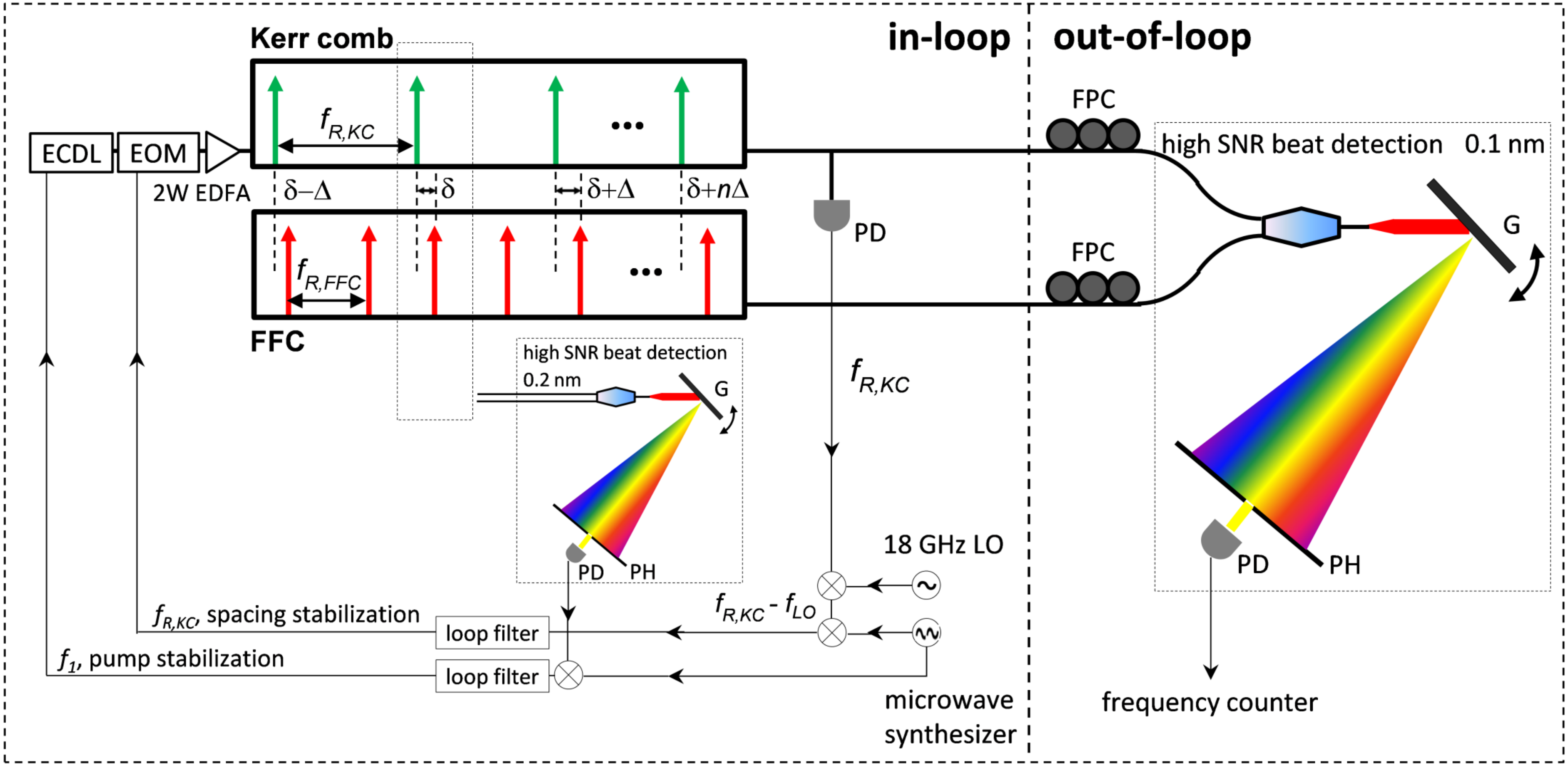
Quantum-noise-limited phase noise has a roll-off of 20 dB/decade and approaches −148 dBc/Hz at 1 MHz offset from the carrier of 17.9 GHz.



Stability of the μcomb oscillator

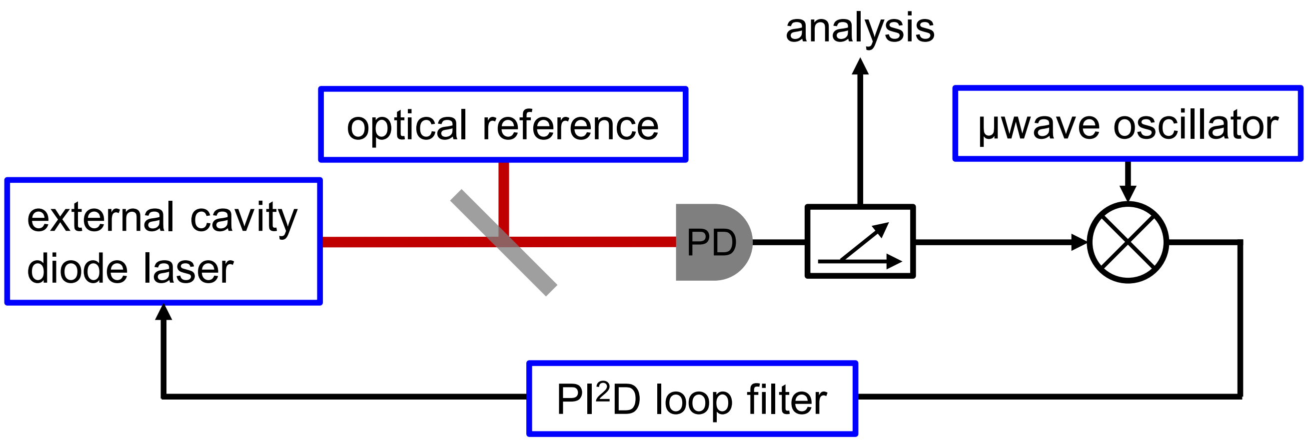
- Pump frequency drift limits the μcomb oscillator's long term frequency stability.
- Allan deviation is improved to 7×10^{-11} at 1 s by a computer-aided pump frequency feedback control.

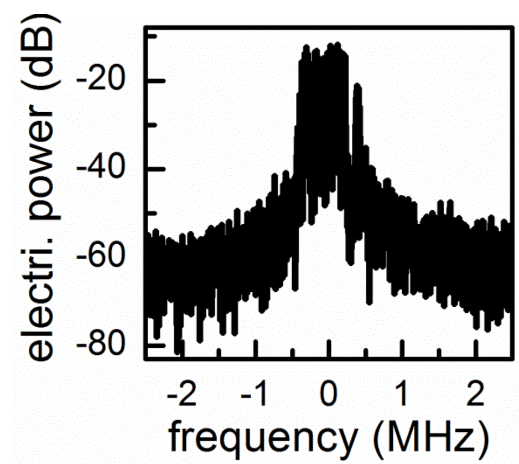


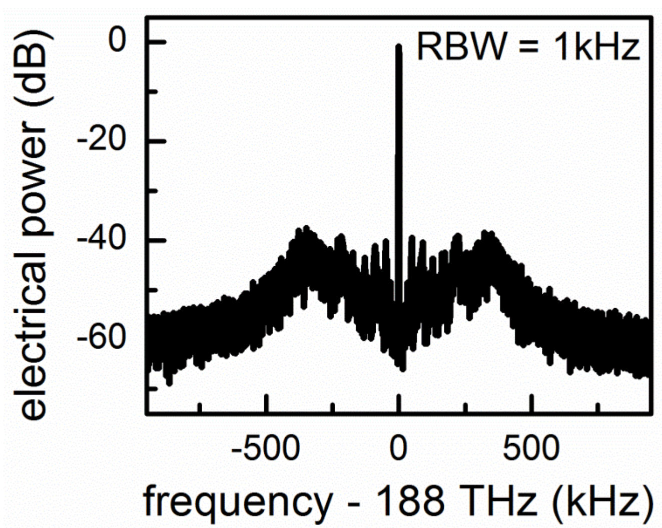


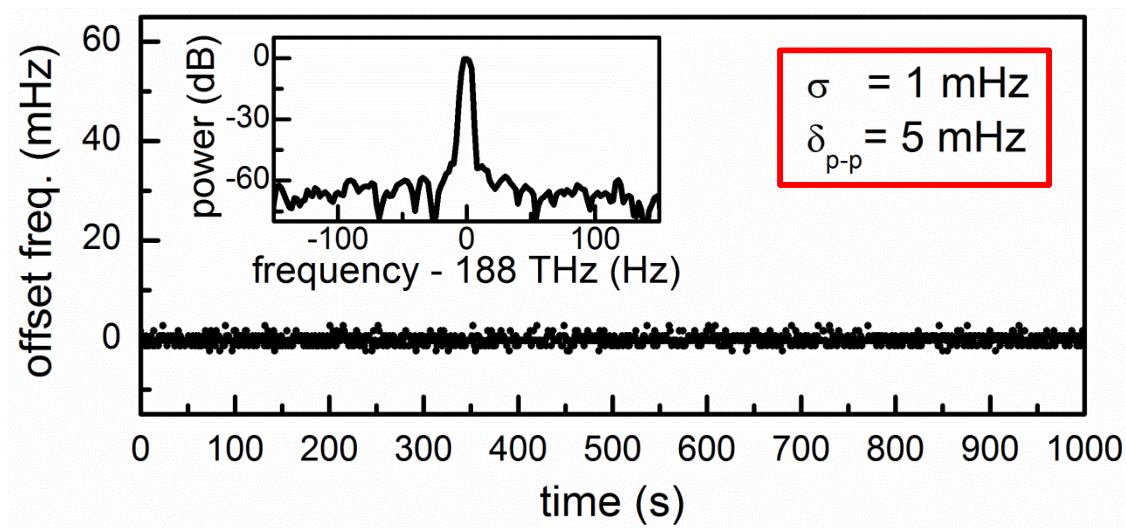
3. High bandwidth comb stabilization achieving a fractional uncertainty of 2.7×10^{-16}
 - Huang *et al.*, *Sci. Adv.* **2**, e1501489 (2016).

Stabilization of f_{opt} via diode current control

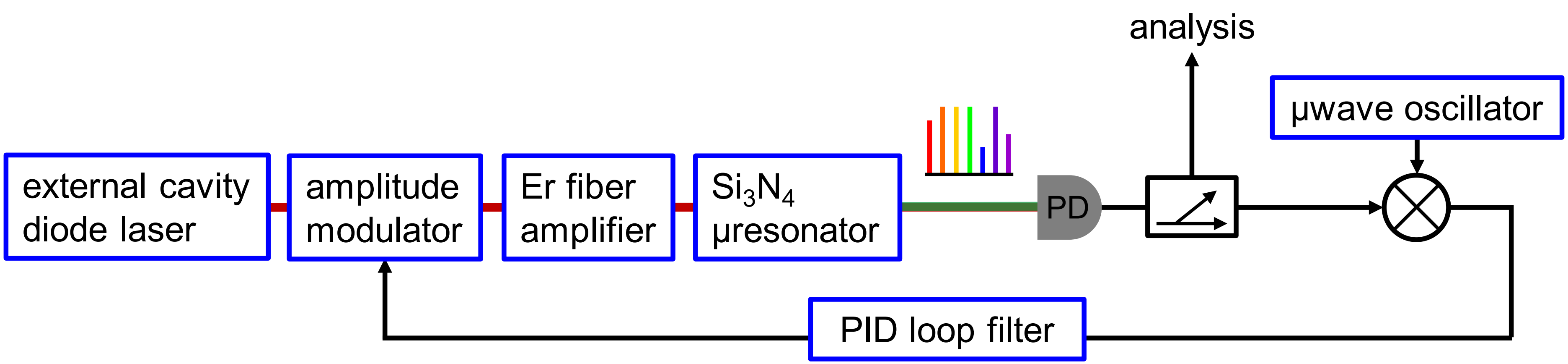


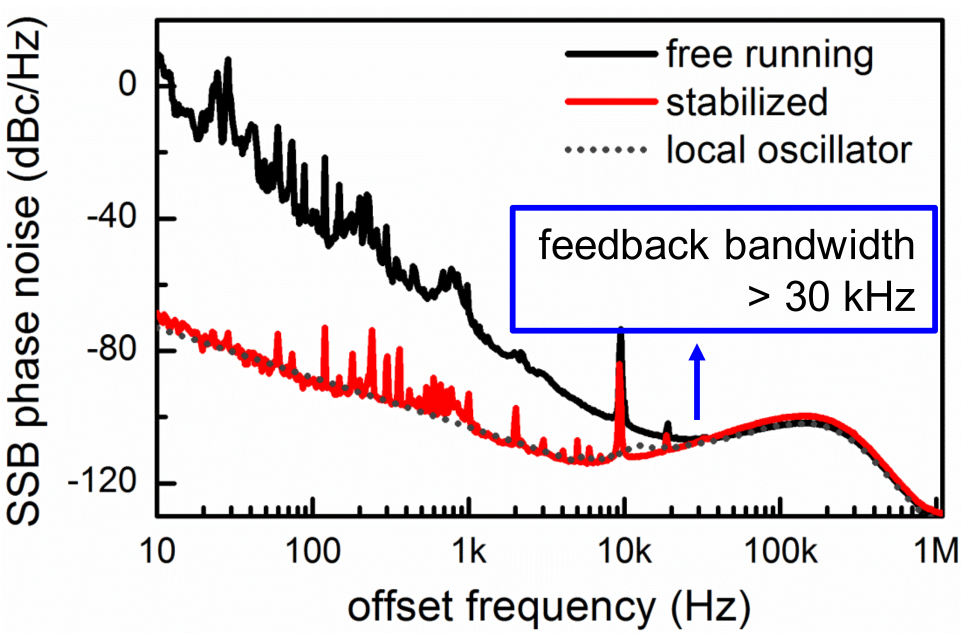


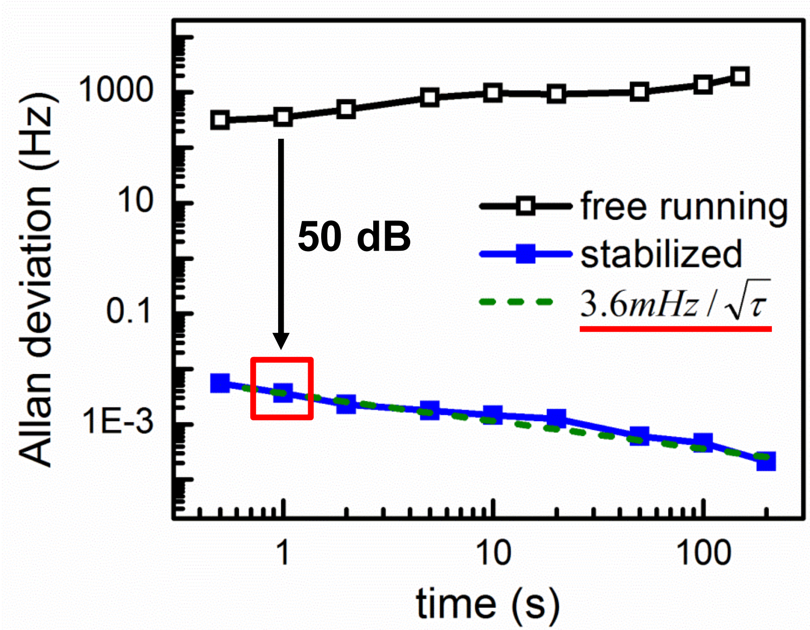


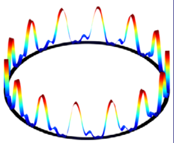


Stabilization of f_{rep} via pump power control

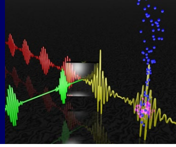




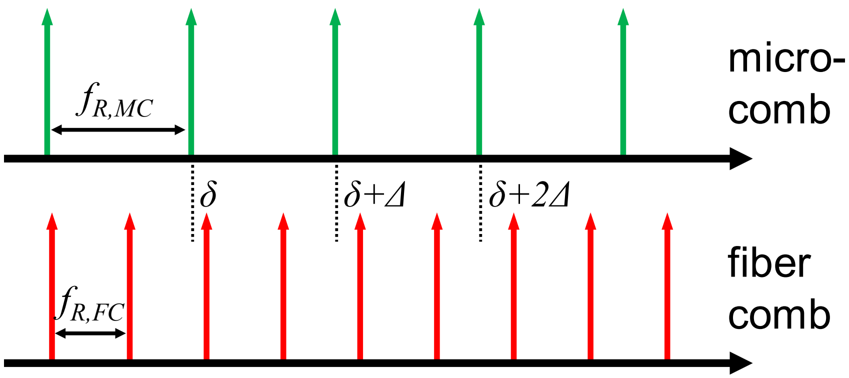


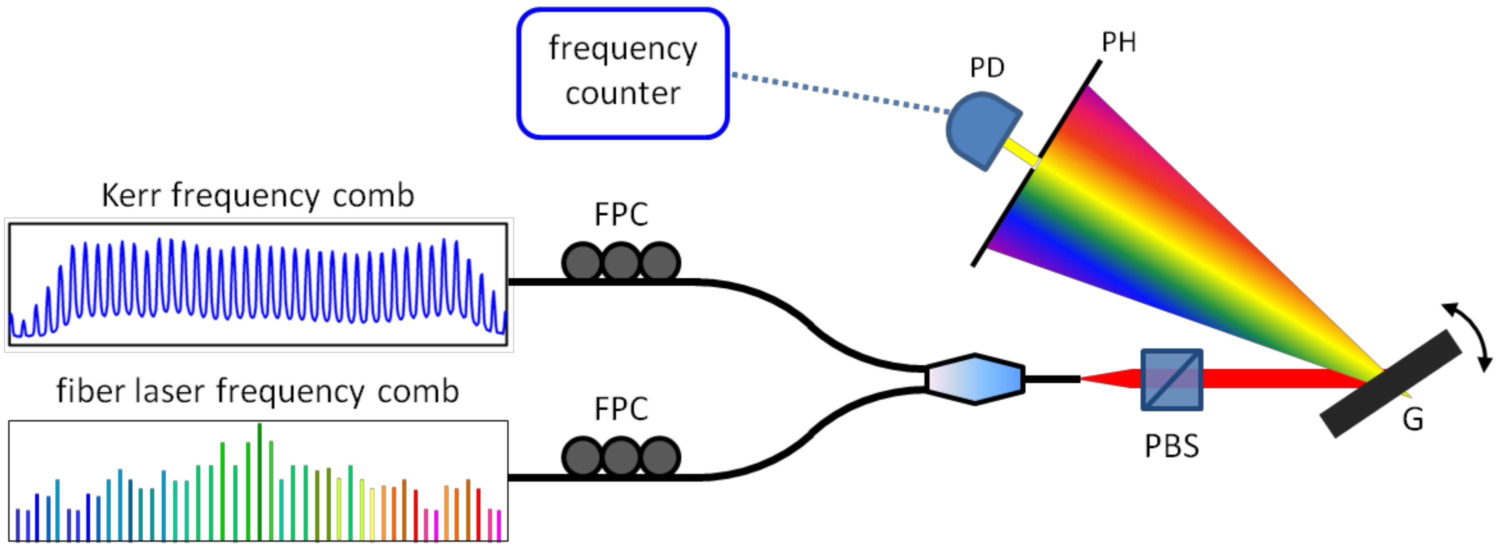


Assessment of the comb frequency uncertainty



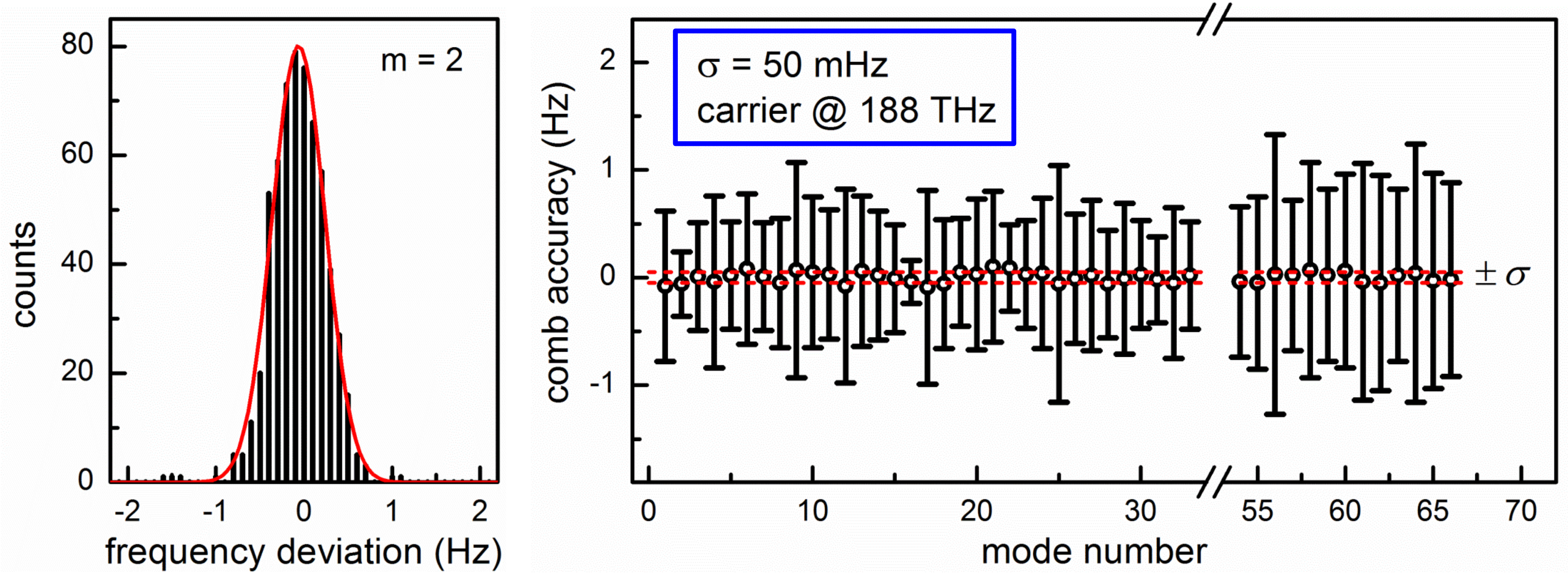
Frequencies of microcomb lines are determined by comparing each line against the state-of-the-art fiber laser frequency comb



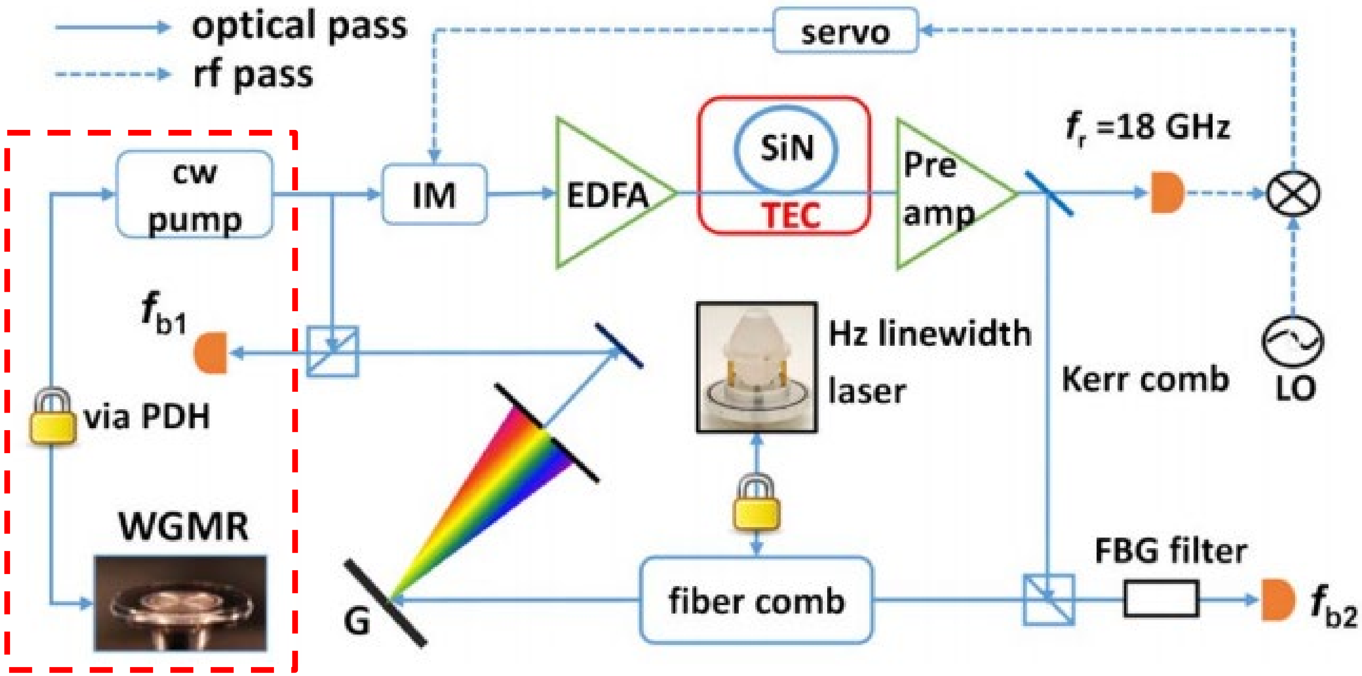


Fractional uncertainty of 2.7×10^{-16}

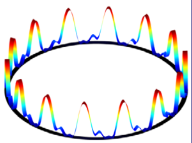
Clockwork using the chip-scale frequency comb as the optical-to-microwave gear can reach a fractional uncertainty of 2.7×10^{-16}.



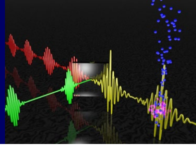
IV. Microresonator stabilized diode laser



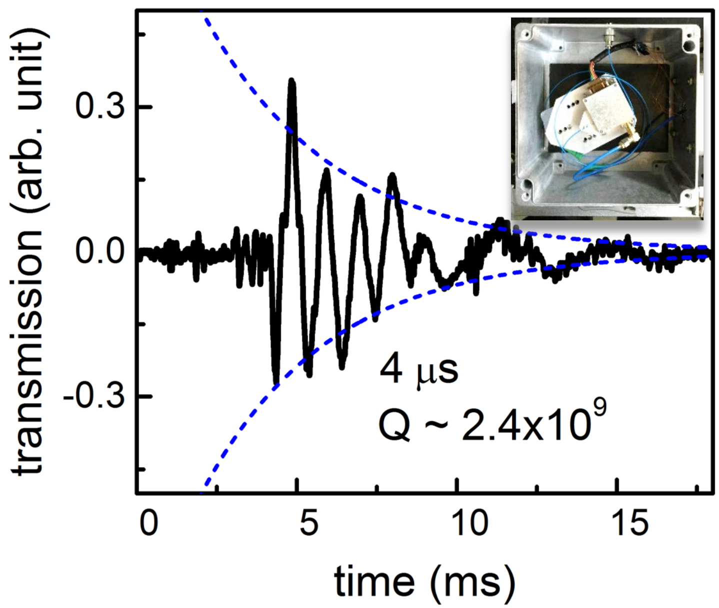
3. High bandwidth comb stabilization achieving a fractional uncertainty of 2.7×10^{-16}
   - Huang *et al.*, *Sci. Adv.* **2**, e1501489 (2016).
4. Microresonator stabilized diode laser at the thermodynamical limit of 1.7×10^{-13}
   - Lim *et al.*, *Opt. Lett.* **41**, 3706 (2016).

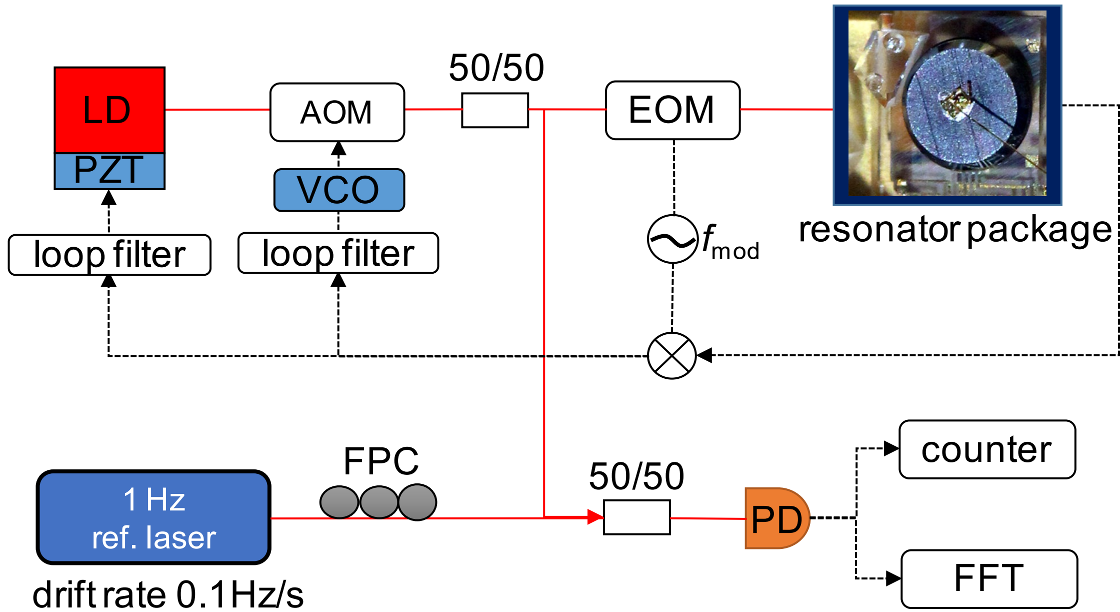


WGM resonator optical reference



The MgF_2 resonator features a high Q of 2.4×10^9 (ring-down time of 4 μs) over a wide spectral range (visible to mid-IR), making it an attractive candidate as an optical reference for laser stabilization.

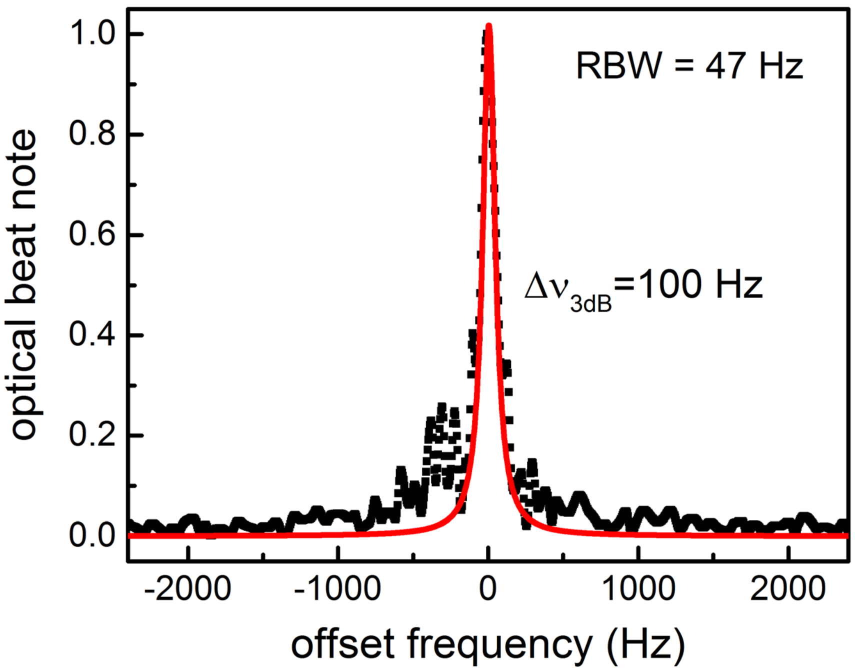


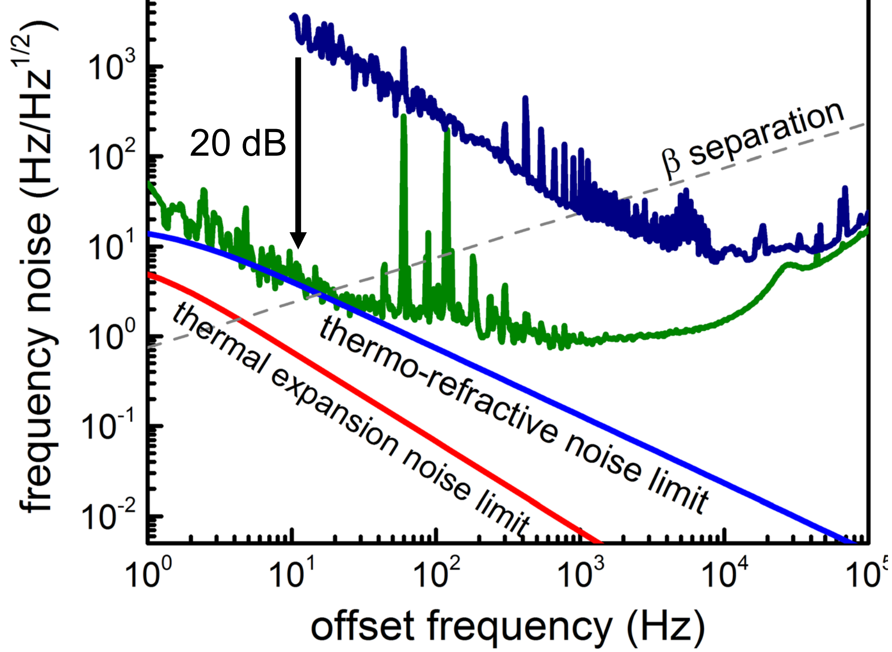


fabricated in OEwaves

Stabilized laser linewidth and frequency noise

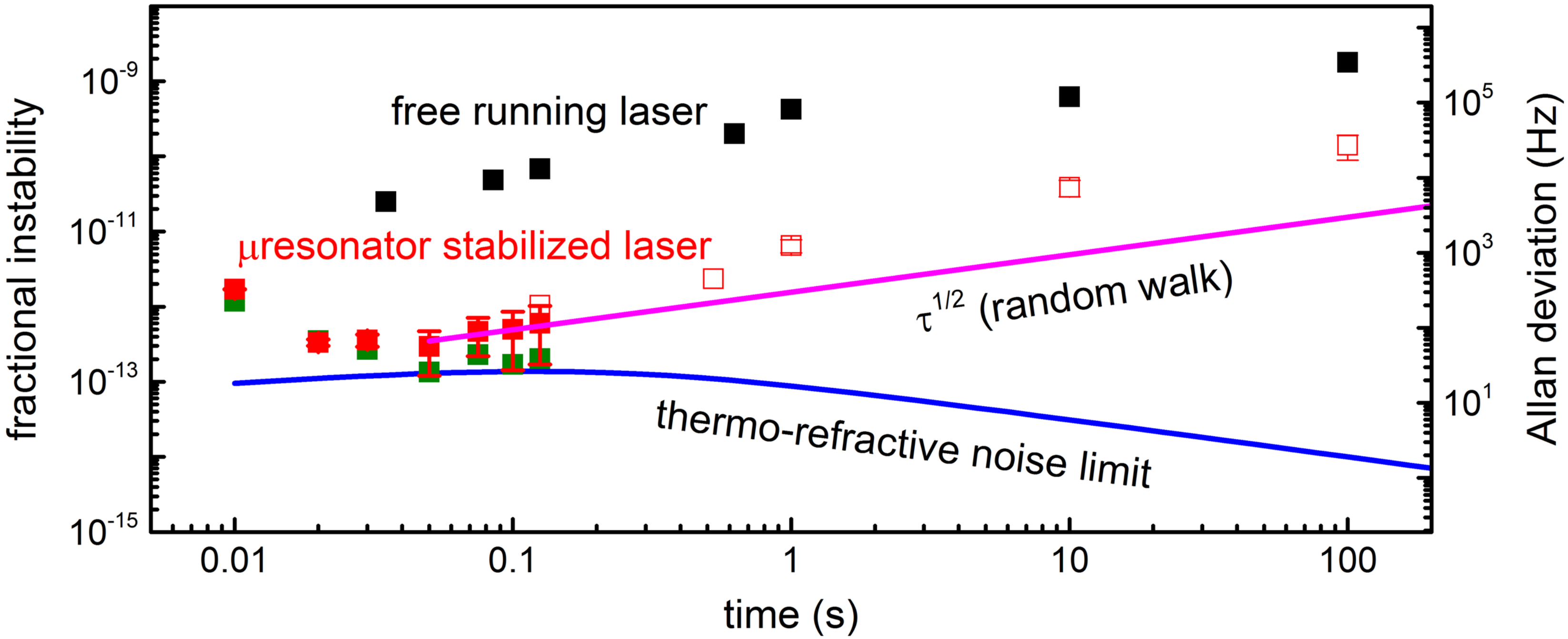
- The stabilized laser linewidth is measured at 100 Hz (25 Hz if the power-line noise is numerically removed).
- The pink frequency noise is a direct consequence of the presence of multiple normal modes of the heat transfer equation in the MgF_2 microresonator.



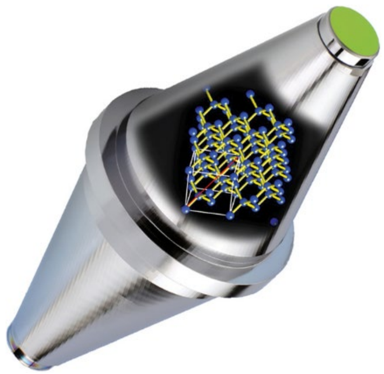


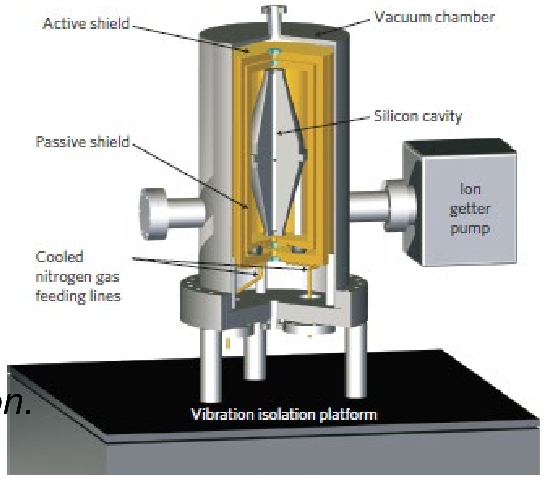
Assessment of the laser frequency instability

- Fractional instability of the stabilized laser frequency reaches the thermo-refractive noise limit of 1.7×10^{-13} at 100 ms.
- Long-term stability deviates from the random walk noise ($\tau^{1/2}$) due to the digitization error of the used thermo-electric cooler.



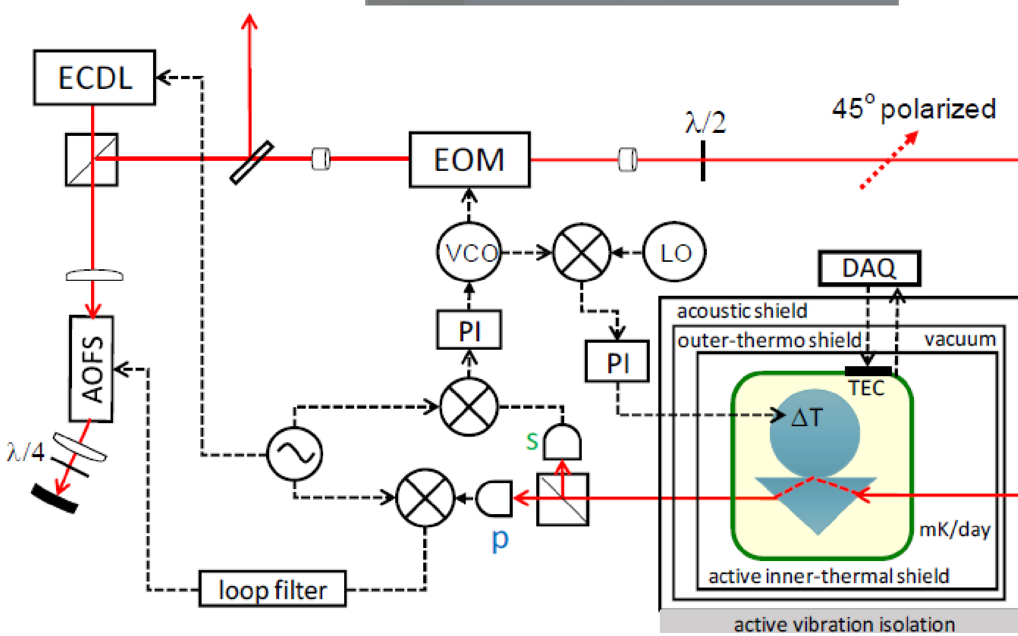
Dual-mode temperature compensation



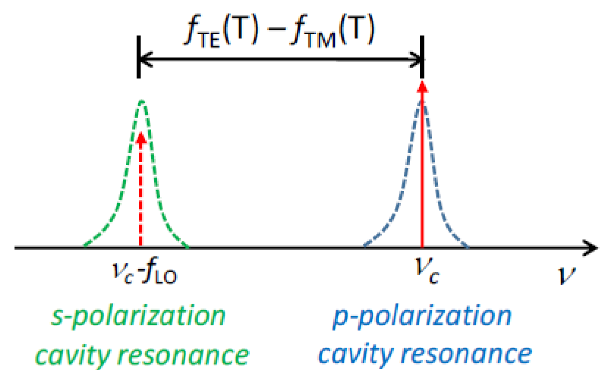


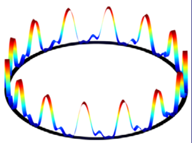
T. Kessler *et al.*, *Nat. Photon.* **6**, 687 (2012).

Going from bulk to chip-scale solution, thermal noise induced resonance shift becomes the dominant noise source and active suppression to sub-μK is necessary.

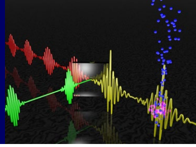


J. Alnis *et al.*, *Phys. Rev. A* **84**, 011804 (2011).

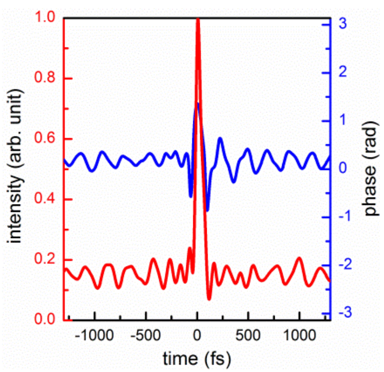


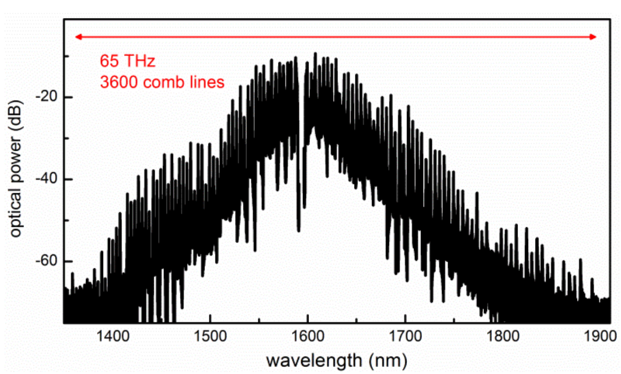


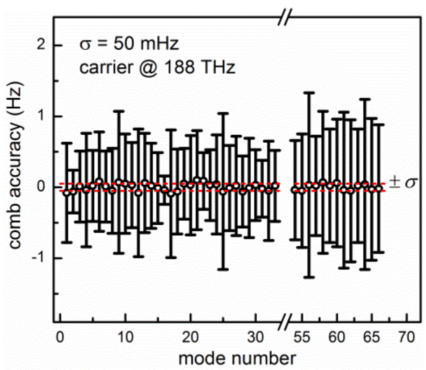
Summary

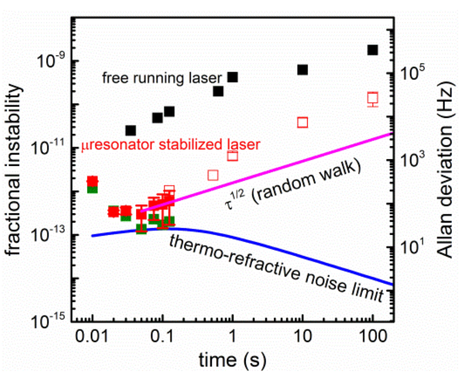


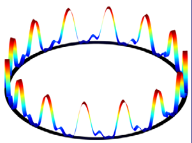
1. Microresonator-based ultrafast light source delivering 74 femtosecond pulse train
   - Huang *et al.*, *Phys. Rev. Lett.* **114**, 053901 (2015).
2. Low noise broadband microcomb containing 3,600 coherent frequency teeth
   - Huang *et al.*, *Sci. Rep.* **5**, 13355 (2015).
3. High bandwidth comb stabilization achieving a fractional uncertainty of 2.7×10^{-16}
   - Huang *et al.*, *Sci. Adv.* **2**, e1501489 (2016).
4. Microresonator stabilized diode laser at the thermodynamical limit of 1.7×10^{-13}
   - Lim *et al.*, *Opt. Lett.* **41**, 3706 (2016).



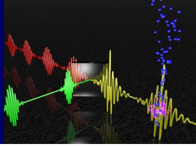




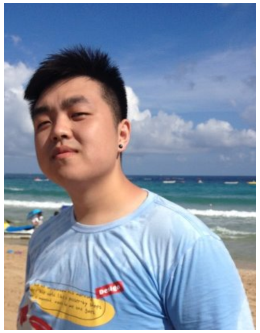




Acknowledgement






Chee Wei Wong | Jinkang Lim | Abhinav Kumar | Hao Liu | Jinghui Yang

Collaborators

- M. Jarrahi, B. Jalali (UCLA)
- A. Matsko, A. Savchenkov, L. Maleki (OEwaves)
- M. Yu, D.-L. Kwong (IME)
- T. Zelevinsky, K. Bergman, H. Krishnaswamy (Columbia)
- H. Zhou (UESTC)
- K. Y. Wong (HKU)

Funding Support

- AFOSR Young Investigator Research program
- DARPA Direct On-chip Digital Optical Synthesizer program