Microresonator based Optical Frequency Combs

V. Brasch, M. Geiselmann, T. Herr, M. Pfeiffer, Caroline Lecaplein, Maxim Karpov, M. Zervas

ML Gorodetksy*, Tobias J. Kippenberg,

EPFL

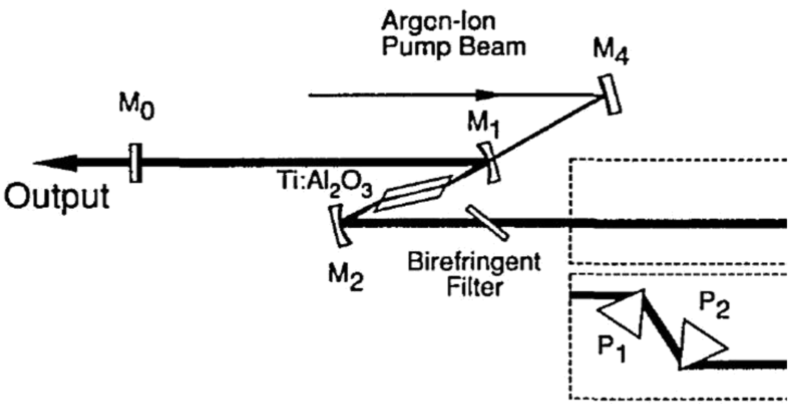
Caltech

3rd November 2015

Worked presented funded under QuASAR, PULSE

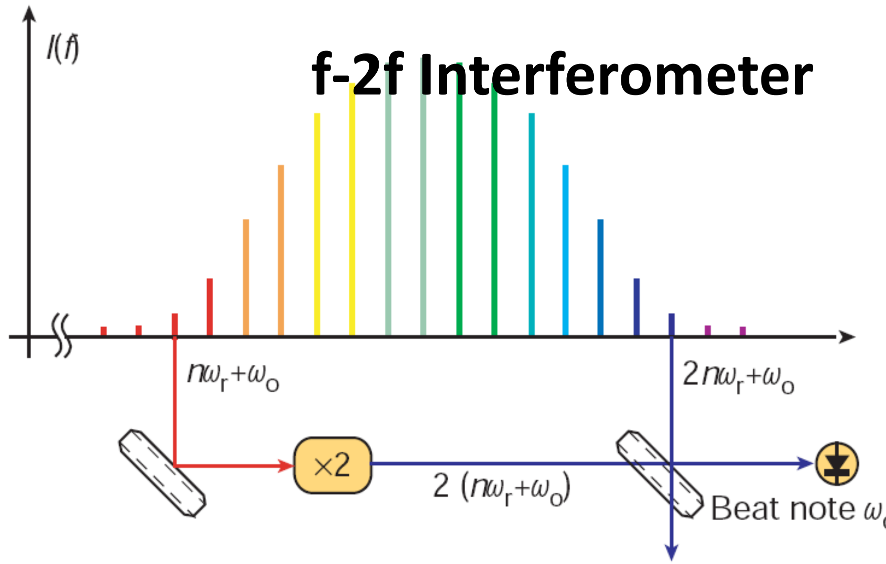
Optical frequency combs

Mode-locked lasers



Spence et al, Optics Letters, 16(1):42–44, January 1991, etc…

f-2f Interferometer



S.T. Cundiff & J. Ye, Rev. Mod. Phys.75, 325 (2003)
Udem, Holtzwarth, Hänsch, Nature, 416, 233 (2003)
H. R. Telle Applied Physics B-Lasers And Optics, 1999.

Nobel Prize Physics 2005:
"for their contributions to the development of laser-based precision spectroscopy, including the optical frequency comb technique"

Direct RF to Optical Frequency Measurements with a. **Femtosecond Laser** Comb.
Scott A. Diddams, David J. Jones, Jun Ye, Steven T. Cundiff, John L. Hall, Science 1999

Discovery of Kerr Comb Generation mechanism

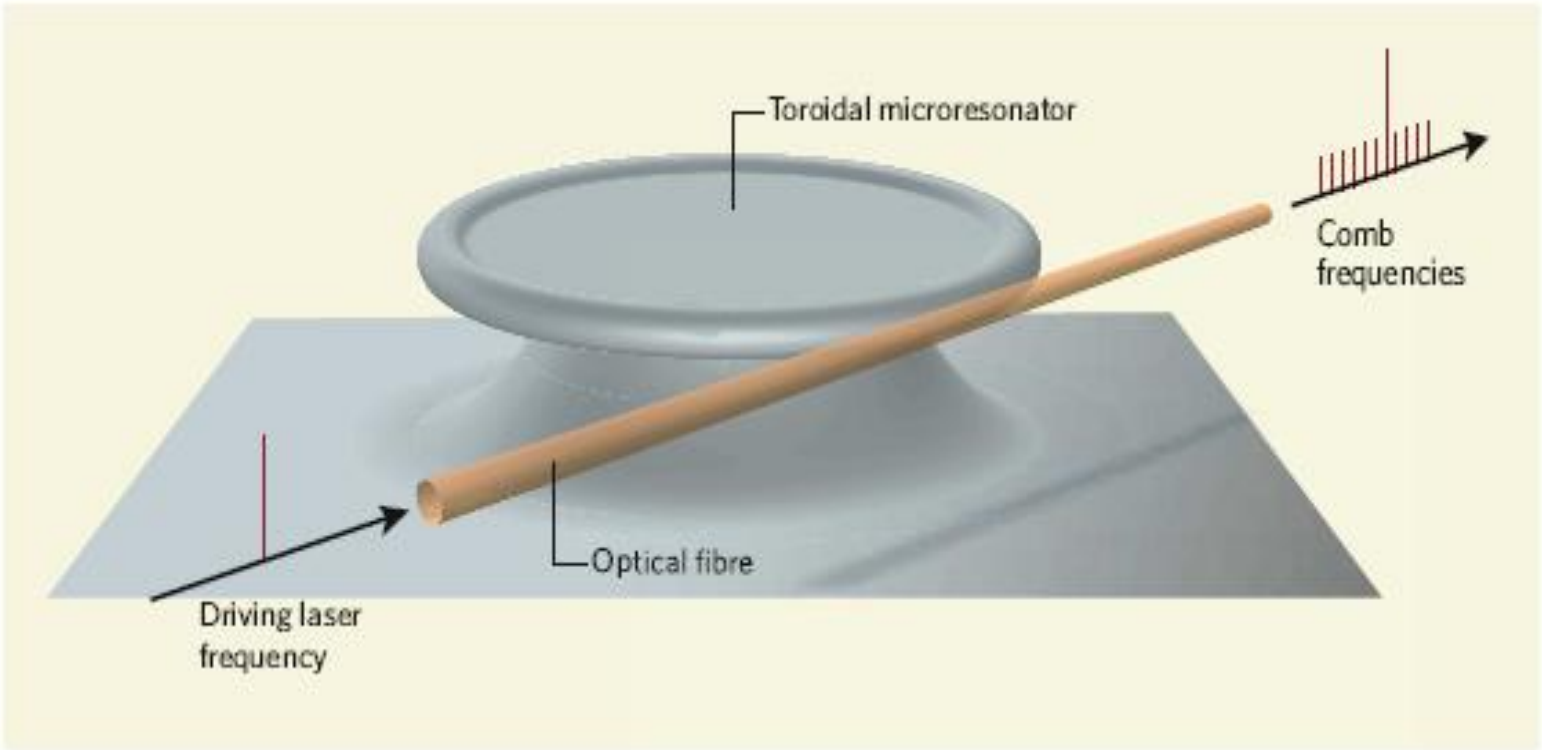
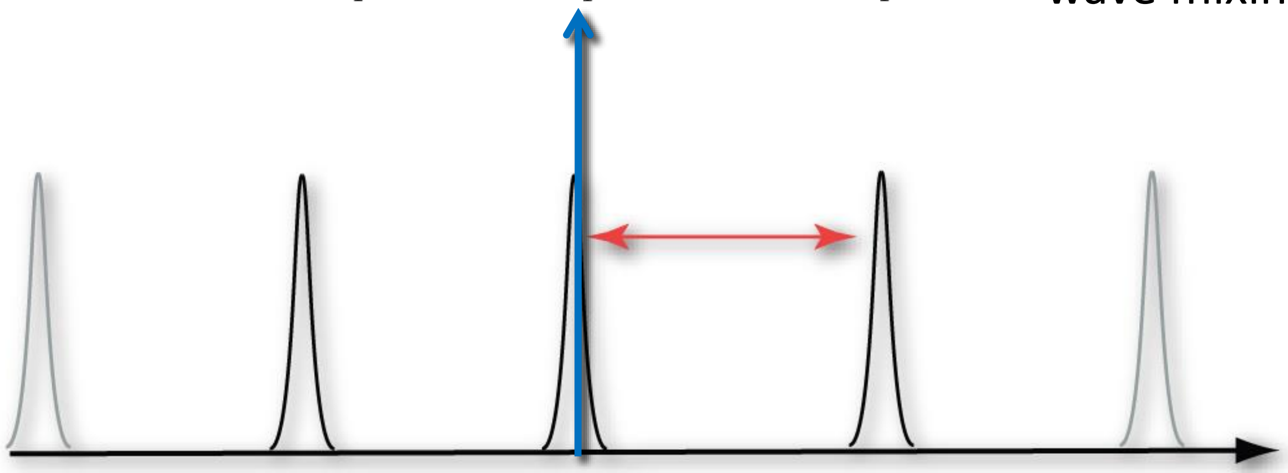


Image credit: S. Cundiff News&Views, Nature, Dec. 20, 2007

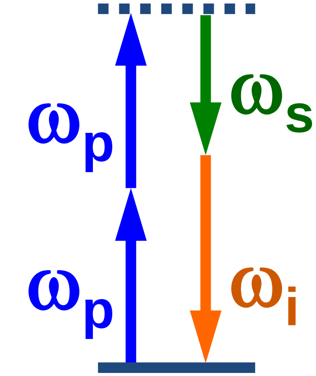
Del Haye,Schliesser,Wilkins, Holzwarth,Kippenberg, Nature, **2007**
Del Haye, Arcizet, Schliesser, Holzwarth, Kippenberg, Phys. Rev. Lett., **2008**
EU & US Patent application "Optical Comb Generator using Microresonators"
TJ Kippenberg, Holtzwarth, Diddams, Science **2011**

Physics of Kerr comb formation process

$\omega_s = \omega_p - \Delta \quad \omega_p \quad \omega_i = \omega_p + \Delta$



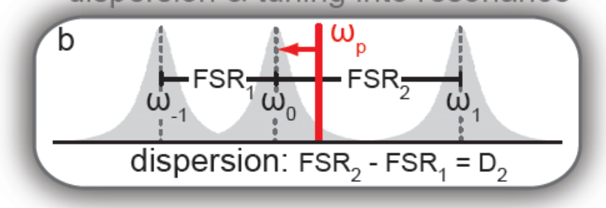
Degenerate four-wave mixing:



$$P^i_{nl} = \epsilon_0 \chi^{(3)} E_p E_p E_s^*$$

$$P_{thresh} \propto V_m / Q^2$$

dispersion & tuning into resonance

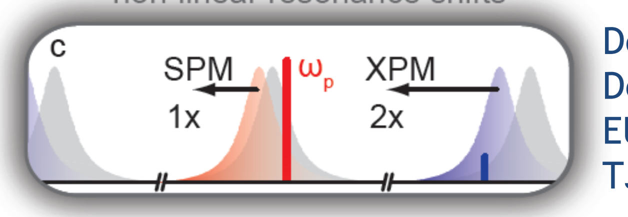


$$\mu = \sqrt{\frac{\kappa}{D_2}}$$

$$\hat{H} = \hbar g_p \hat{a}_p \hat{a}_p \hat{a_s}^\dagger \hat{a_i}^\dagger$$

$$g = \frac{\hbar \omega_0^2 c n_2}{n_0^2 V_{\text{eff}}}$$

non-linear resonance shifts



Del Haye,Schliesser,Wilkins, Holzwarth,Kippenberg, Nature, **2007**
Del Haye, Arcizet, Schliesser, Holzwarth, Kippenberg, Phys. Rev. Lett., **2008**
EU & US Patent application "Optical Comb Generator using Microresonators"
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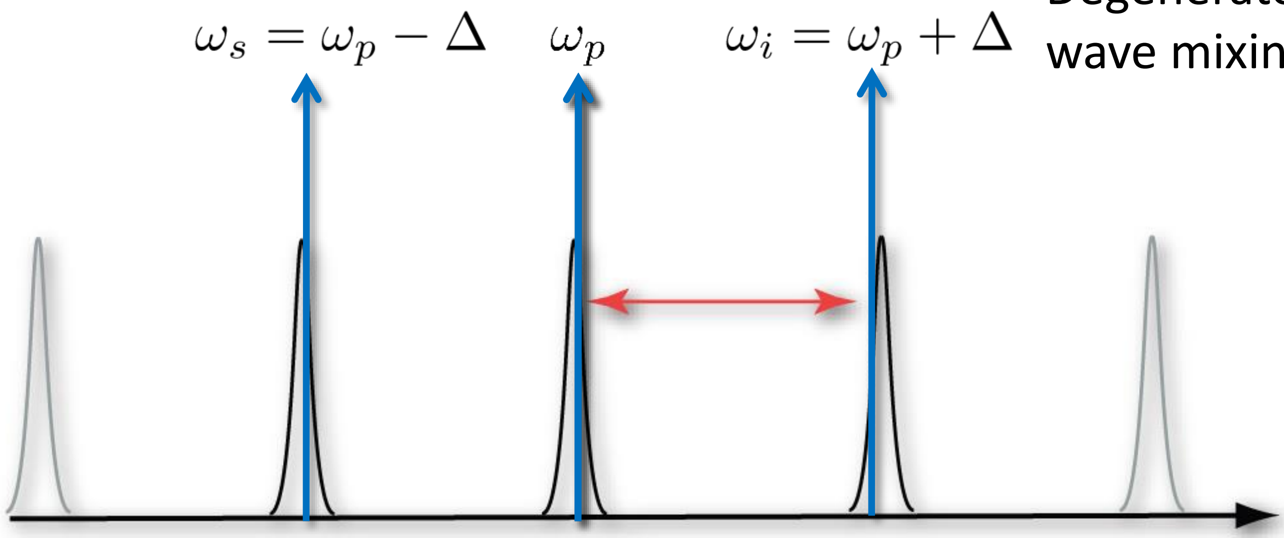
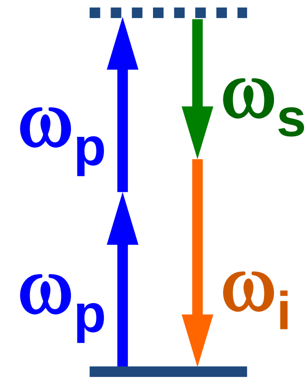
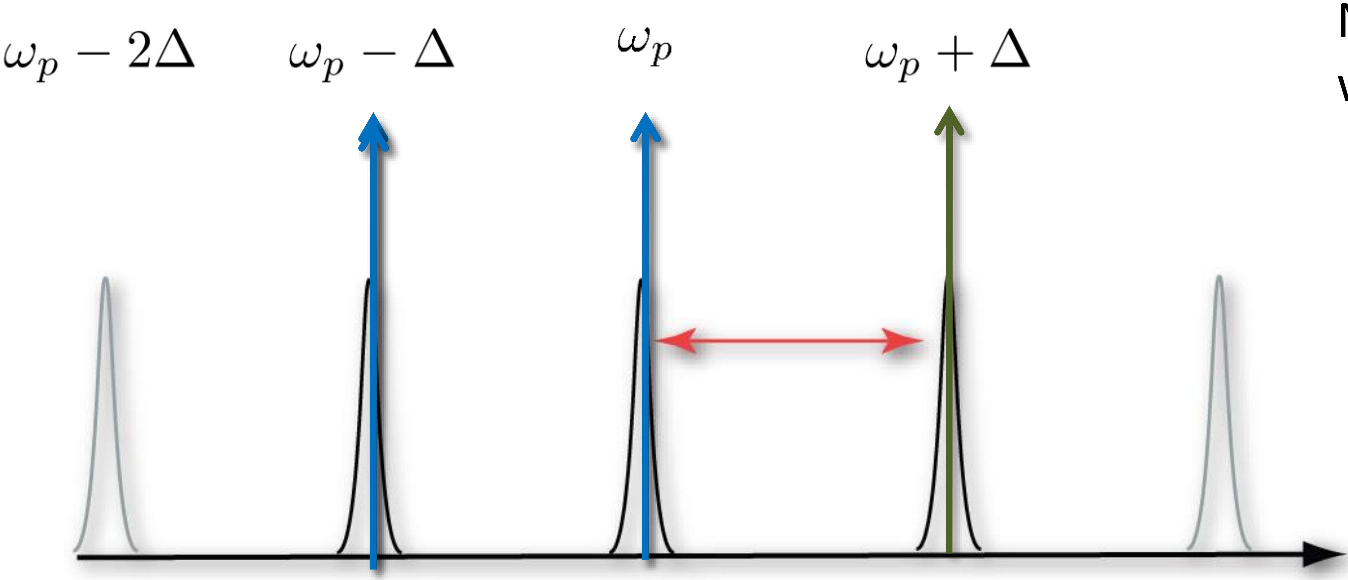
Physics of Kerr comb formation process



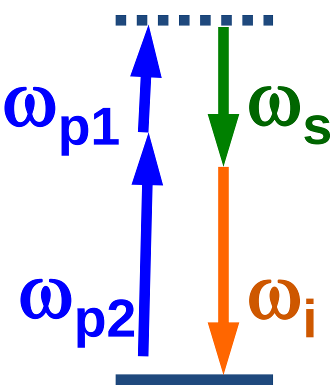
Degenerate four-wave mixing:



$$P_{nl}^{i} = \epsilon_0 \chi^{(3)} E_p E_p E_s^*$$

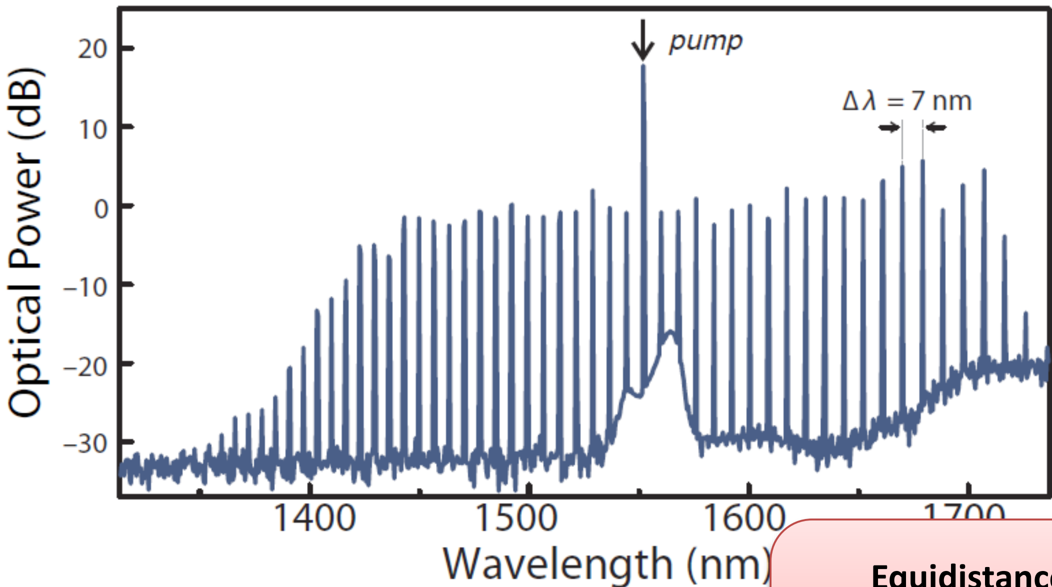


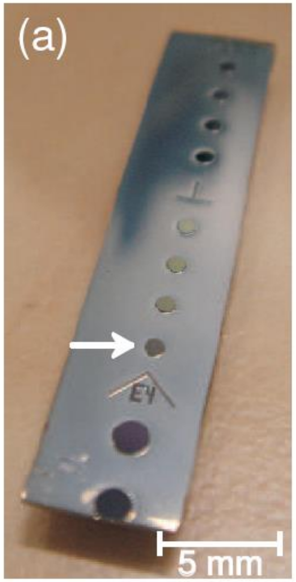
Non degenerate four-wave mixing:



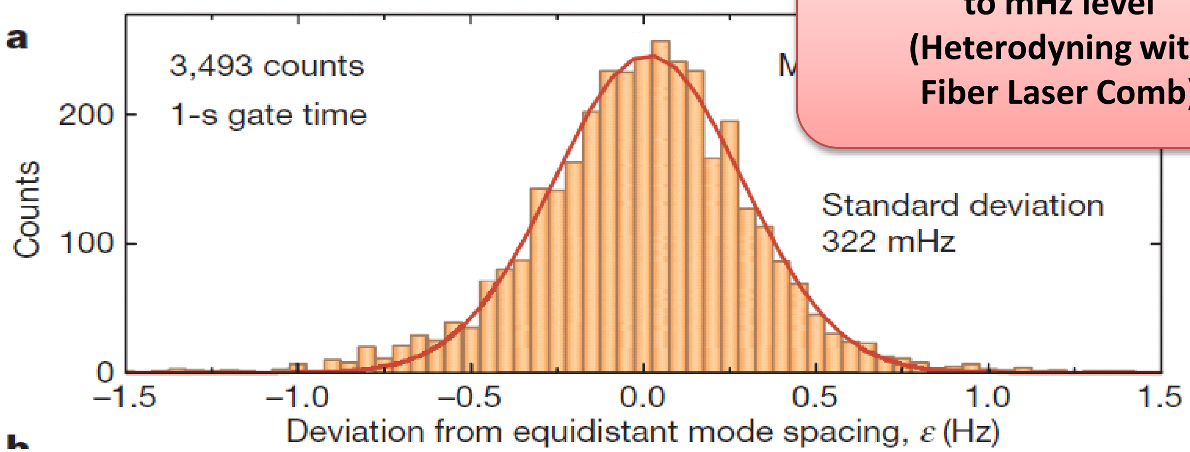
$$P_{nl}^{i2} = \epsilon_0 \chi^{(3)} E_p E_i E_s^*$$

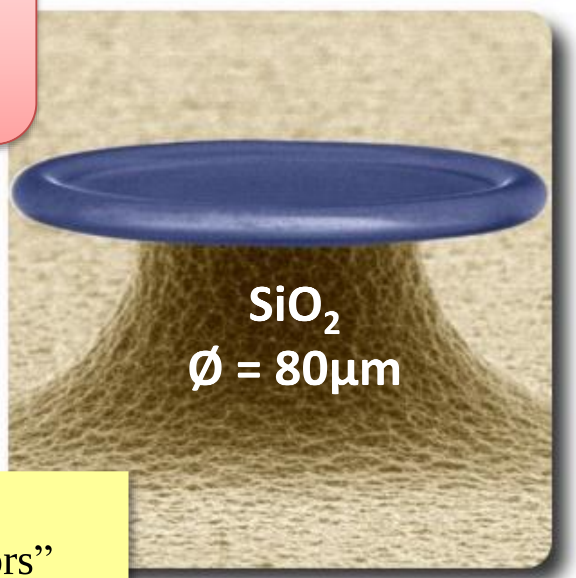
Discovery of Kerr Comb Generation mechanism





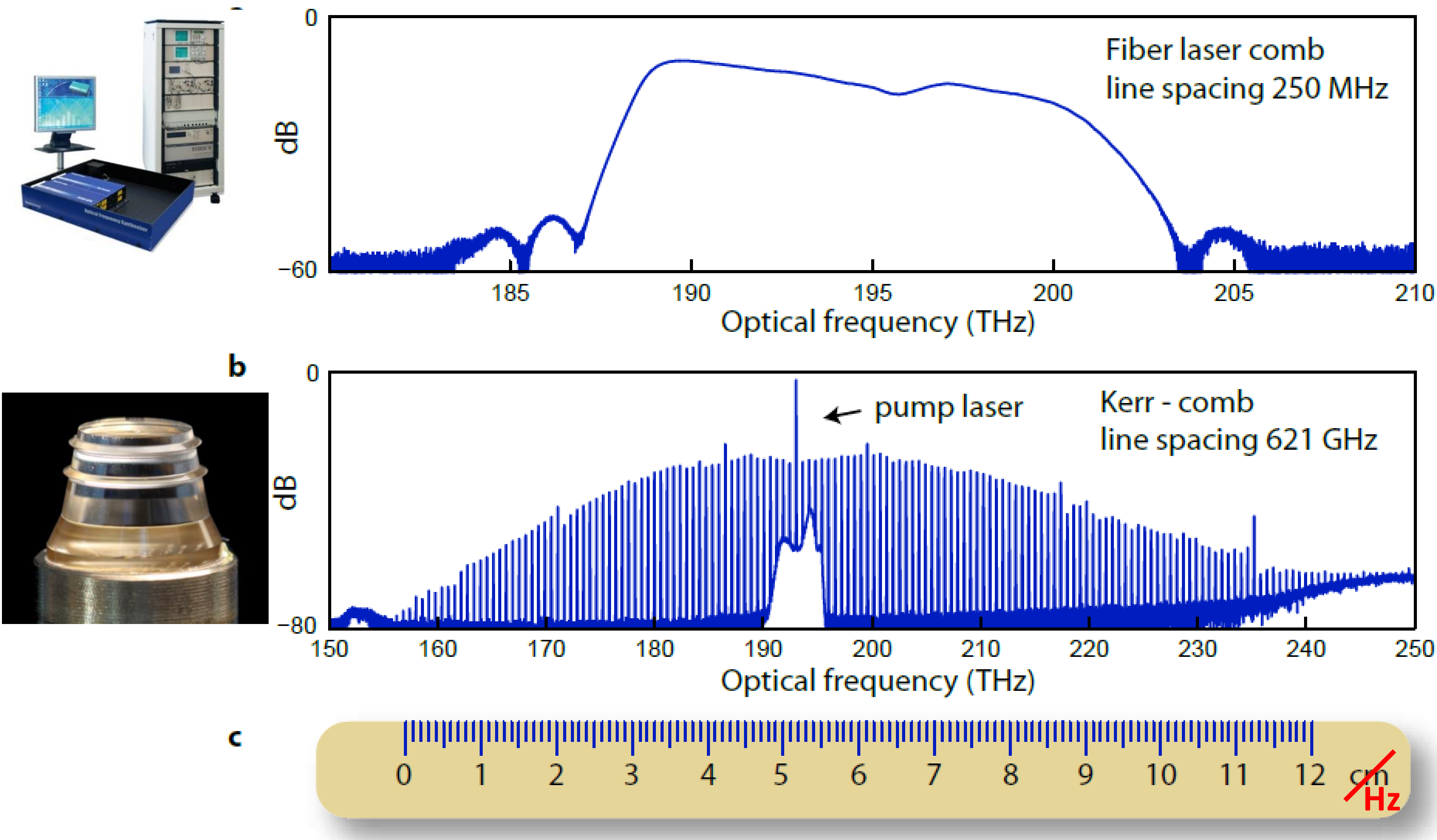
Equidistance verified to mHz level (Heterodyning with Fiber Laser Comb)





Del Haye, Schliesser, Wilkins, Holzwarth, Kippenberg, Nature, **2007**
EU & US Patent application “Optical Comb Generator using Microresonators”
TJ Kippenberg, Holtzwarth, Diddams, Science **2011**

Kerr Comb Generation



Field of Microresonators Comb Generation

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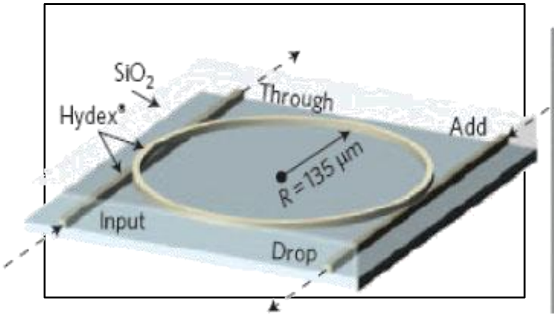
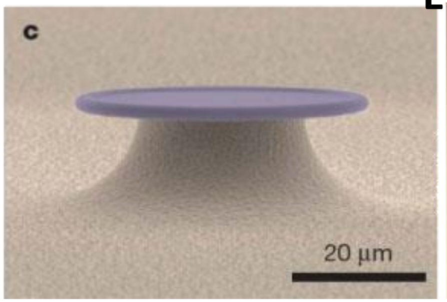
Hydex



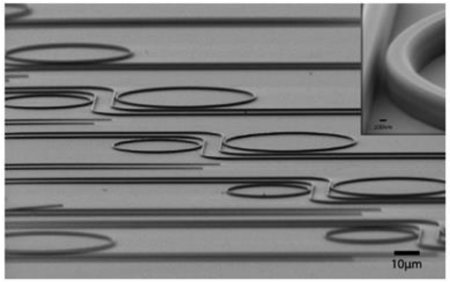
Silicon Nitride (Cornel, NIST, EPFL)

Fused Silica Caltech, MPG

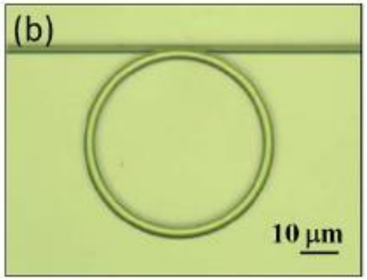


CaF_2 JPL, OEWaves FEMTO, EPFL

Diamond (Harvard)



AlN (Yale)



Silica, Caltech

<u>Progress in the field:</u>

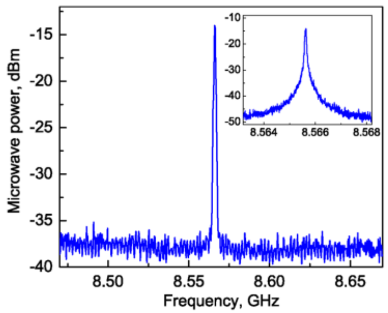
- Phase stabilization
- Octave spanning combs
- GHz repetition rates
- Waveform generation
- Mid IR Combs
- Kerrr combs Clocks
- ….

Review: TJ Kippenberg, R. Holtzwarth, S.A. Diddams, *Science* (2011) Microresonator based Optical Frequency Combs“

Advances in Kerr optical Frequency Combs

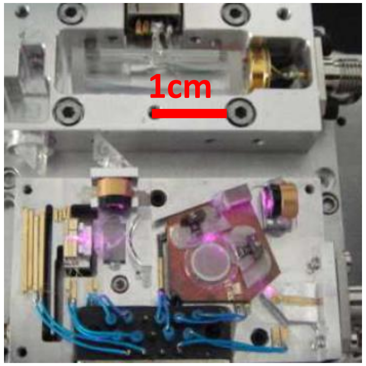
Low Noise Microwaves

Savchenkov et al., PRL 2004



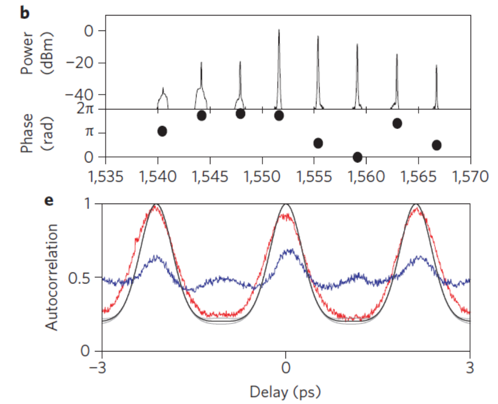
Miniature Optical Clock

Savchenkov et al., arXiv 2013
S. Papp, Optica (2014)



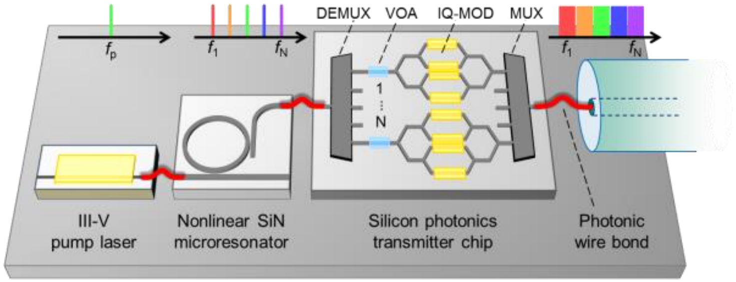
Optical Waveform Synthesis

Ferdous et al., Nature Photonics 2011



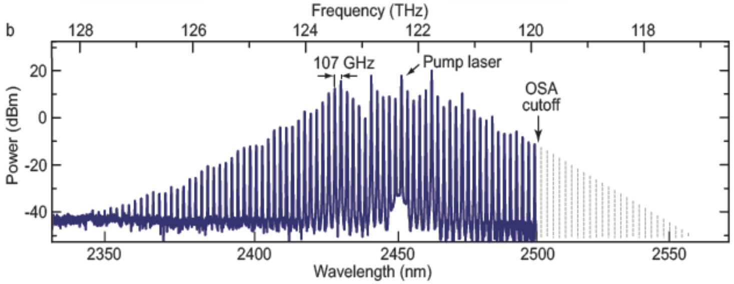
High-Capacity Telecom Kerr-Comb as Channel Generator

Pfeifle et al., Nature Photonics 2014
OFC 2012, OFC 2013

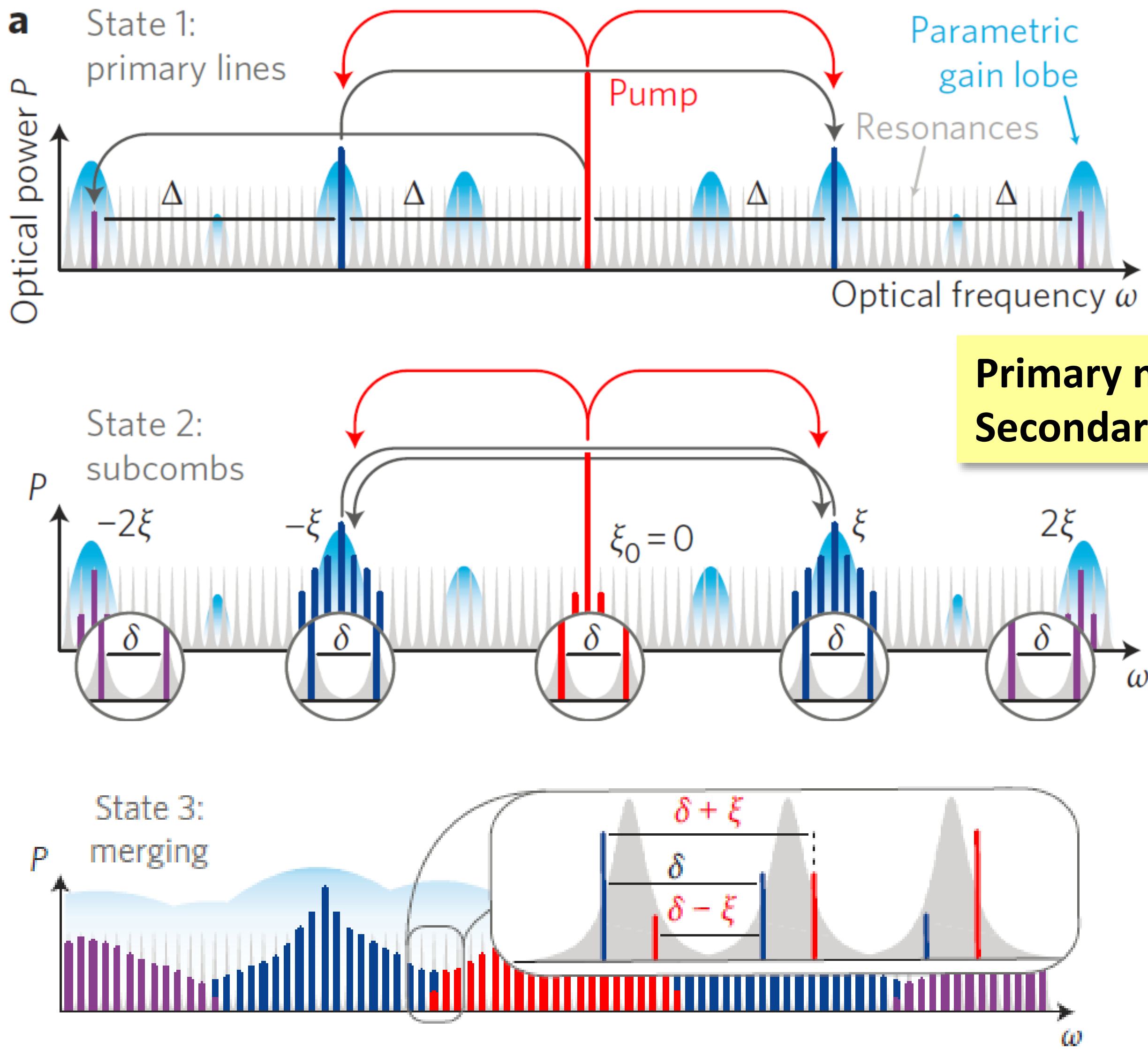


VIS and Mid-IR combs

Wang et al., Nature Comm 2013
Savchenkov et al. Nature Photonics 2011
Geata, Lipson et al. Nature Comm. 2015



Comb formation process



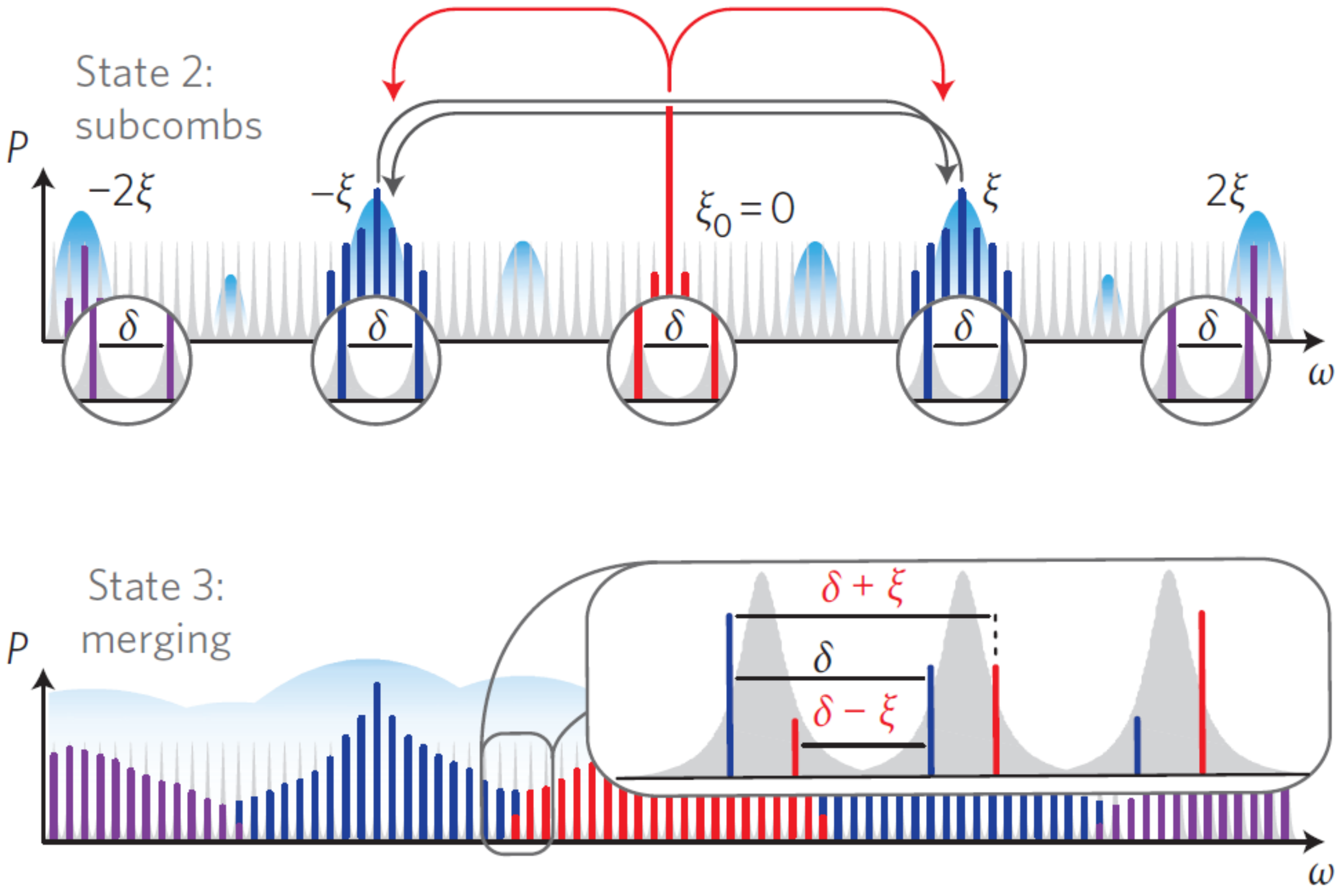
$$\mu = \sqrt{\frac{\kappa}{D_2}}$$

Primary mode spacing: Δ
Secondary mode spacing: δ

$$\Delta \neq n\delta$$

Herr, T. et al. (2012). *Nature Photonics 6*, 480 (2012)

Subcomb formation process



$$\mu = \sqrt{\frac{\kappa}{D_2}}$$

Sub-combs lead to noise

Primary mode spacing: Δ
Secondary mode spacing: δ

The spacings Δ and δ are generally not commensurate:
Subcombs with different offset frequencies

Herr et al. *Nature Photonics 2012*

Coherent Comb formation regimes

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1. Intrinsically Low Noise Regime: No subcombs when

$$\mu_0 \approx \sqrt{\frac{\kappa}{D_2}} < 1$$

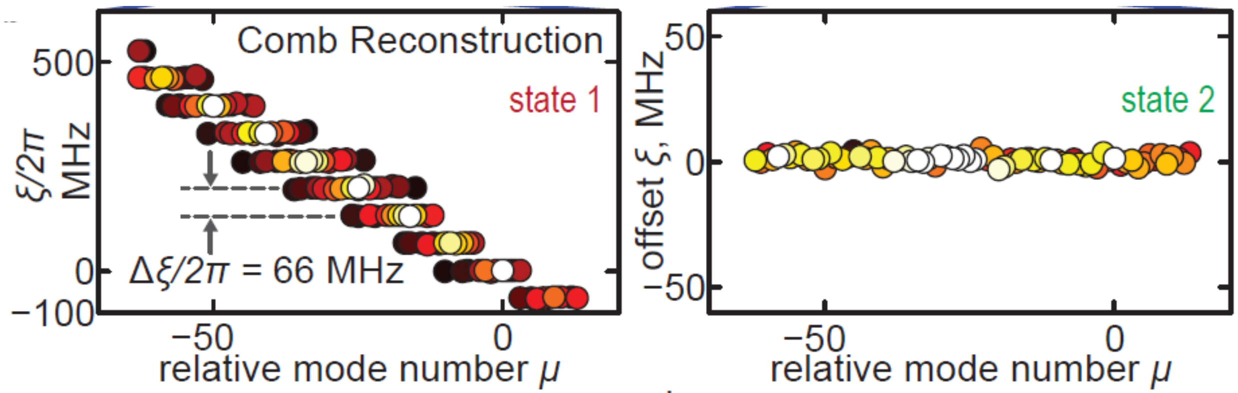
2007

- P. Del Haye, et al. Nature 2007
- Wang et al. Nat. Comm. 2012
- …

2011

2. "δ-Δ-matching":

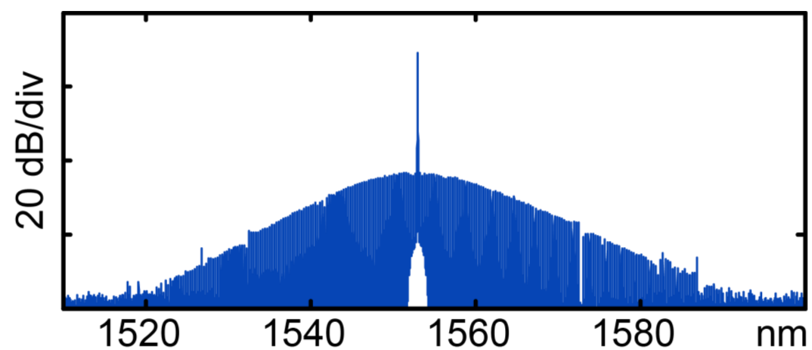
- T. Herr et al., Nat. Photon. (2012)
- Saha et al. Optics Express (2012)
- Del Haye, PRL (2014)



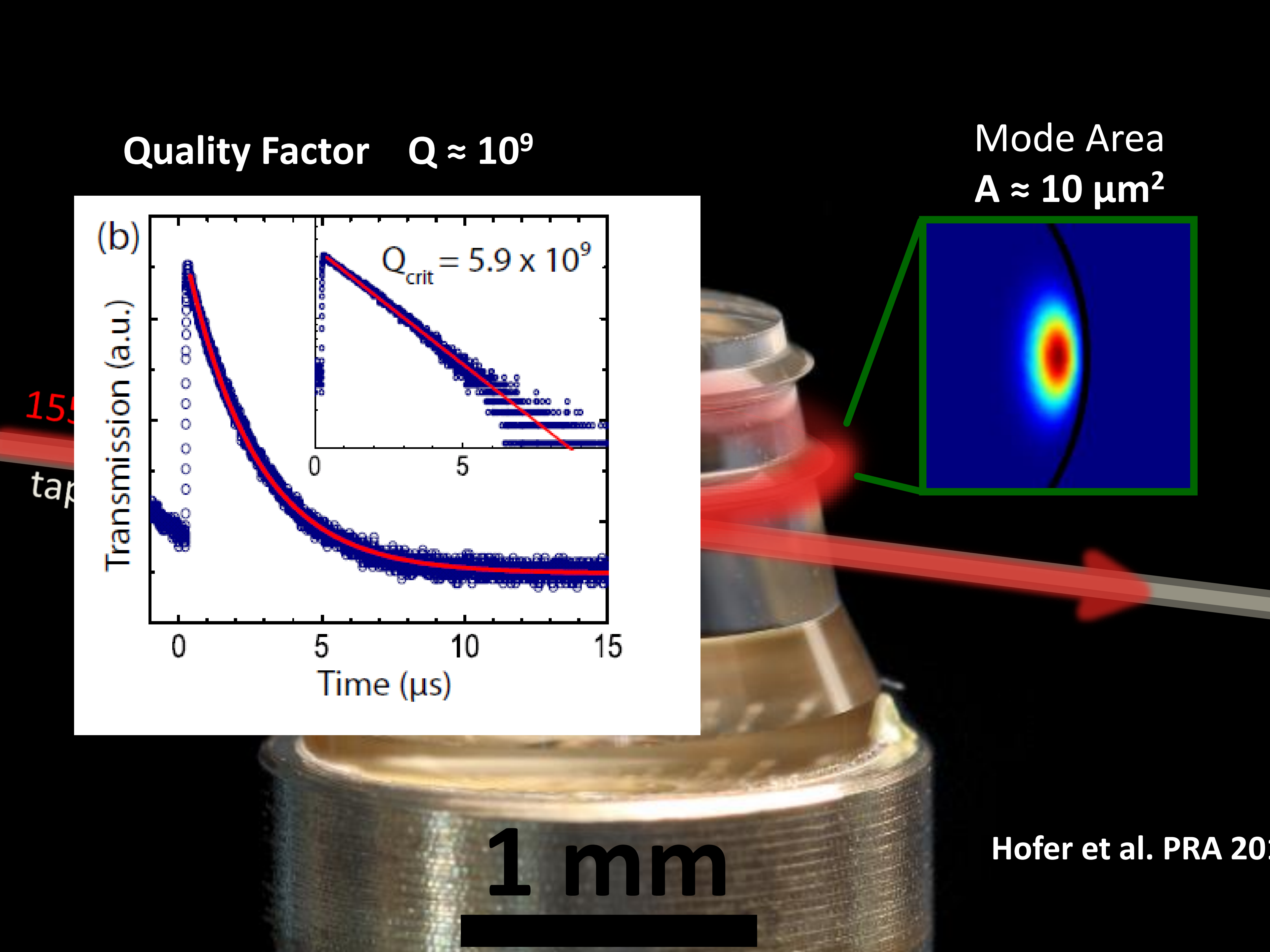
2013

3. Soliton Regime:

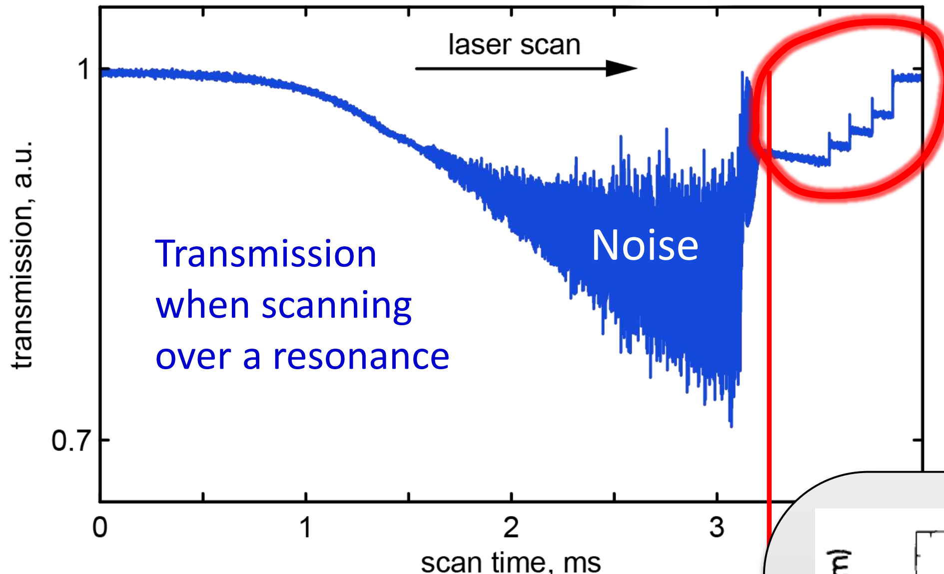
- T. Herr et al., Nat. Photon. (2014)
- B. Brasch arXiv 2014
- Coen et al. 2014
- ….

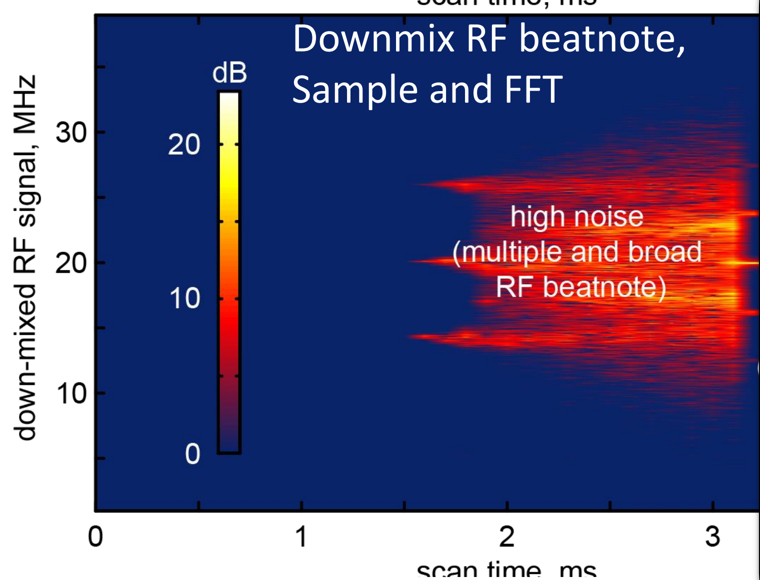



MgF_2
1 mm

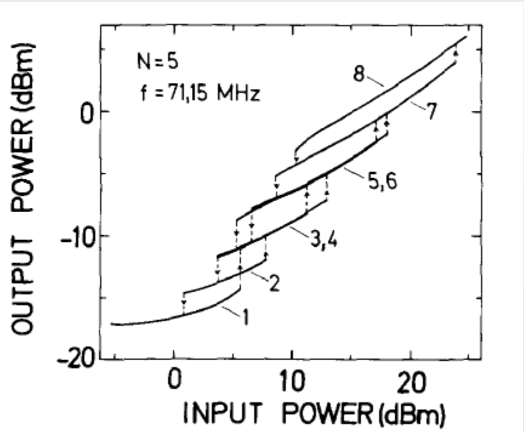

Quality Factor Q ≈ 10^9
Mode Area
A ≈ 10 μm^2
(b)
Transmission (a.u.)
Q_{crit} = 5.9 x 10^9
0
5
0
5
10
15
Time (μs)
1 mm
Hofer et al. PRA 20

Observation of low phase noise comb states





T. Herr et al., *Nature Photonics* (2014)



A. Gasch, B. Wedding, and D. Jager. Multistability and soliton modes in nonlinear microwave resonators. (1984)

Numerical Simulation

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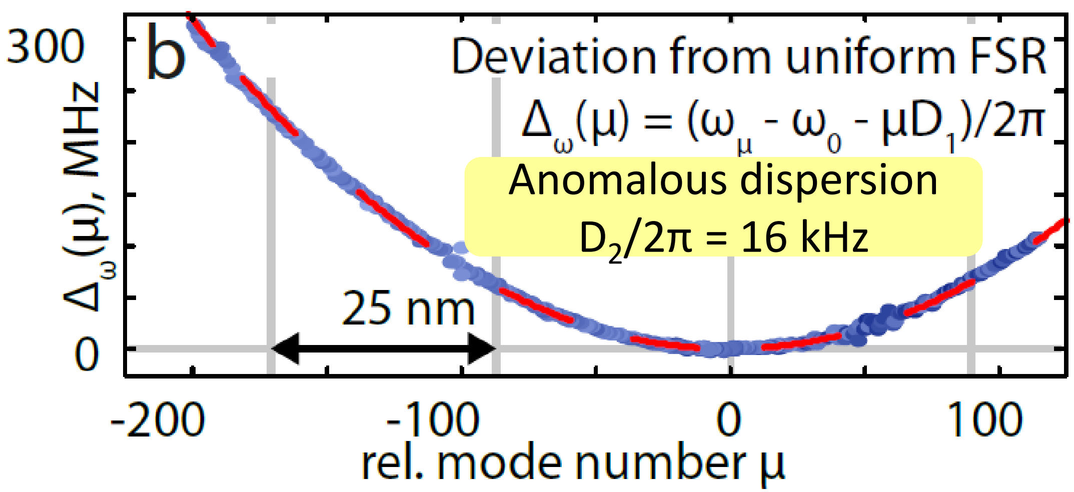
Numerical propagation of **nonlinear coupled mode equations**:

(Chembo et al., PRA 2010)

$$\frac{\partial A_\mu}{\partial t} = \underbrace{-\frac{\kappa}{2}A_\mu}_{\text{Cavity loss}} + \underbrace{\delta_{\mu 0}\sqrt{\eta\kappa}s_{\text{in}}e^{-i(\omega_p-\omega_0)t}}_{\text{Driving laser}} + \underbrace{ig\sum_{\mu',\mu'',\mu'''} A_{\mu'}A_{\mu''}A^*_{\mu'''}e^{-i(\omega_{\mu'}+\omega_{\mu''}-\omega_{\mu'''}-\omega_\mu)t}}_{\text{Kerr-nonlinearity (SPM/XPM, FWM)}}$$

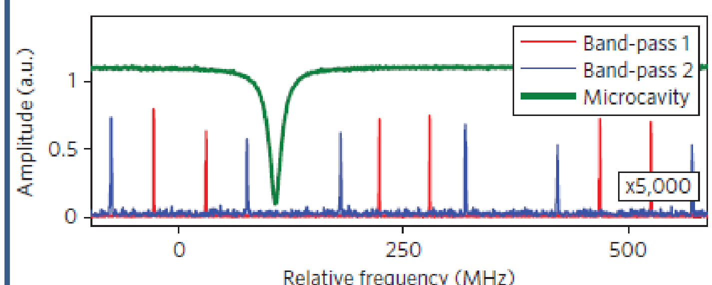
Dispersion: $\omega_\mu = \omega_0 + D_1\,\mu + \frac{1}{2}D_2\,\mu^2 +$

Kerr coefficient: $g = \frac{\hbar\omega_0^2 c n_2}{n_0^2 V_{\text{eff}}}$



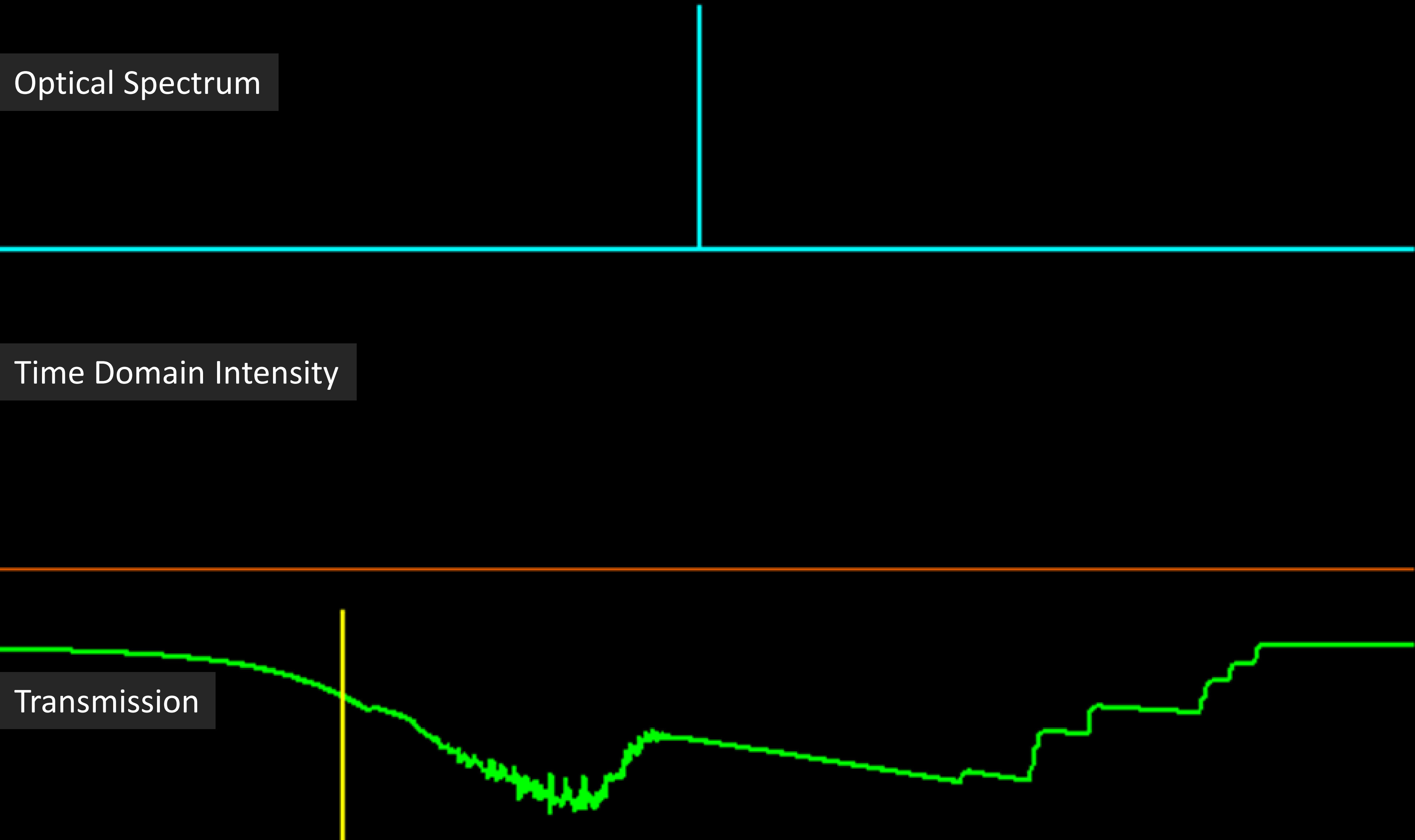
T. Herr et al., Nature Photonics 2014 (arXiv, 2012)

Frequency comb calibrated dispersion measurement



Del'Haye, Nat. Photon, 2011

Simulated Laser Scan



T. Herr et al., Nature Photonics 2014 (arXiv, 2012)

Simulated Laser Scan

T. Herr et al., Nature Photonics 2014

Temporal dissipative cavity solitons

Nonlinear Coupled Mode Equations (Simulation)

equivalent

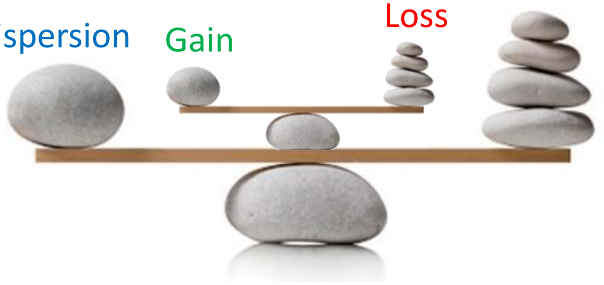
Matsko et al. Optics Letters 2011

Review on dissipative solitons: P. Grelu, Ackmediev Nat. Phot. 2013

Damped driven NLS / Lugiato-Lefever equation

$$i\frac{\partial\Psi}{\partial\tau}+\frac{1}{2}\frac{\partial^2\Psi}{\partial\theta^2}+|\Psi|^2\Psi=(-i+\zeta_0)\Psi+if.$$

Lugiato & Lefever, PRL 1987



Collaboration with **Prof. M. Gorodetsky**
M.V. Lomonosov Moscow State University

Wabnitz , Optics Letters 1993
Barashenkov et al., PRE 1996

Solitons are stable solutions:

$$\Psi(\phi)\simeq C_1+C_2\cdot\sum_{j=1}^{N}\mathrm{sech}\left(\sqrt{\frac{2(\omega_0-\omega_p)}{D_2}}(\phi-\phi_j)\right)$$

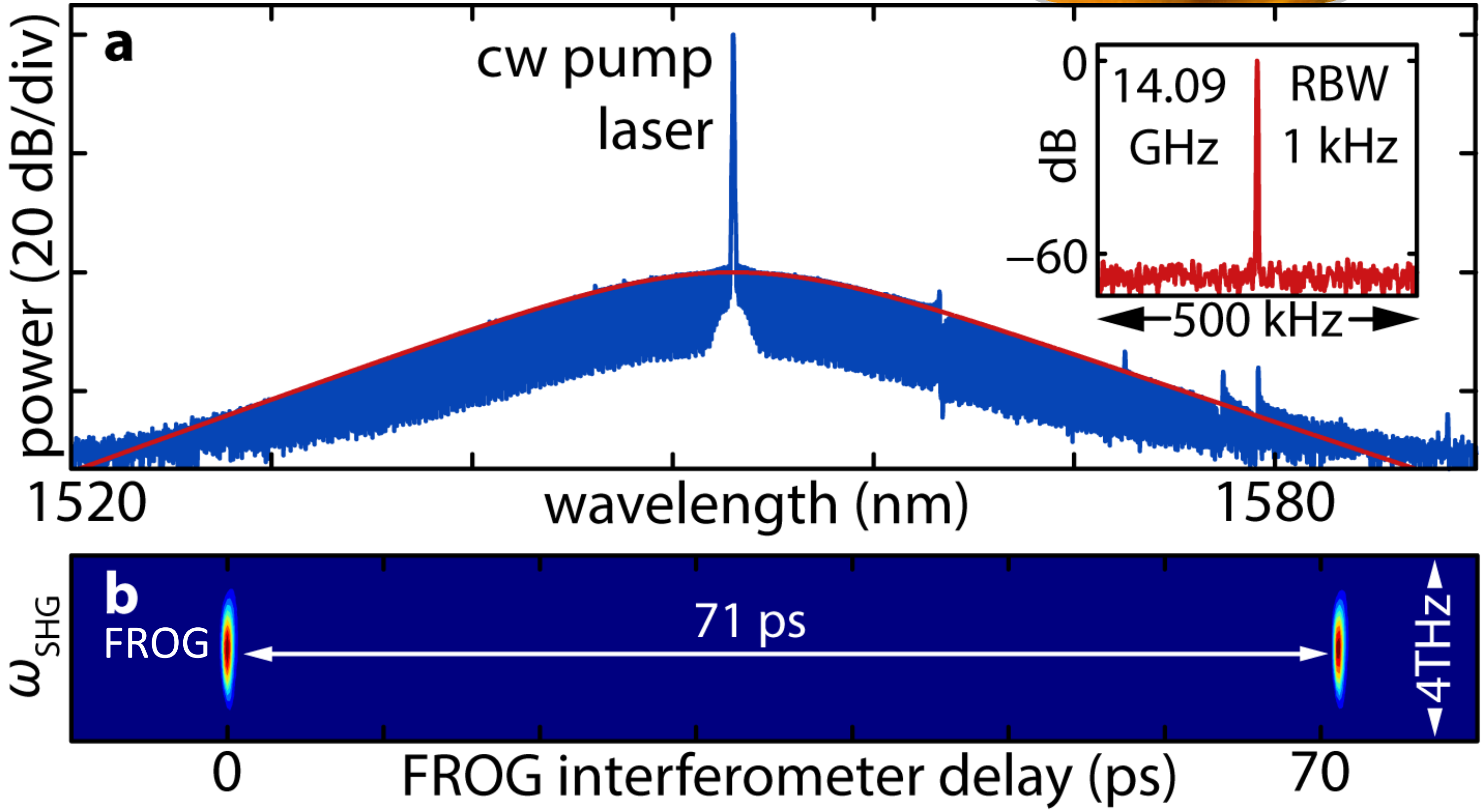
Temporal width:

$$\Delta t_{\min}^{\mathrm{FWHM}}\approx 2\sqrt{\frac{-\beta_2}{\gamma\mathcal{F}P_{\mathrm{in}}}},$$

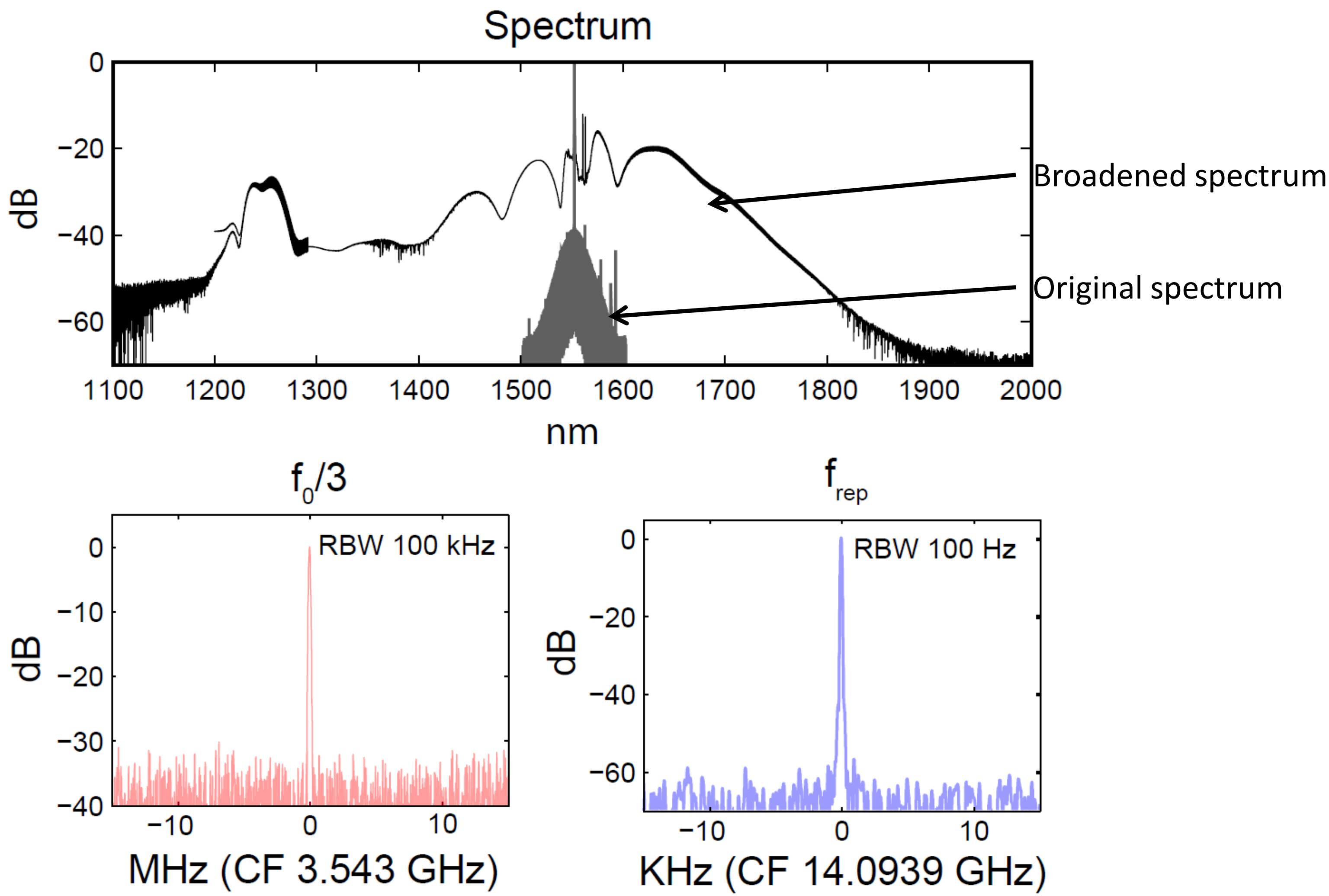
First prediction of solitons in microresonators: Leo, Coen, Halterman et al. *Nat. Photon.* 2010

Temporal single soliton generation in a crystalline resonator

112 fs pulse duration
14 GHz repetition rate



Counting the Cycles of Light using a self referenced crystalline resonator comb



J. Jost et al., **Optica 2015**

$$f_n = n \cdot f_{rep} + f_0$$

Generation of low noise Microwaves using a Soliton State

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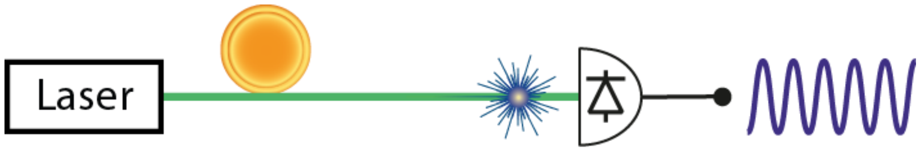
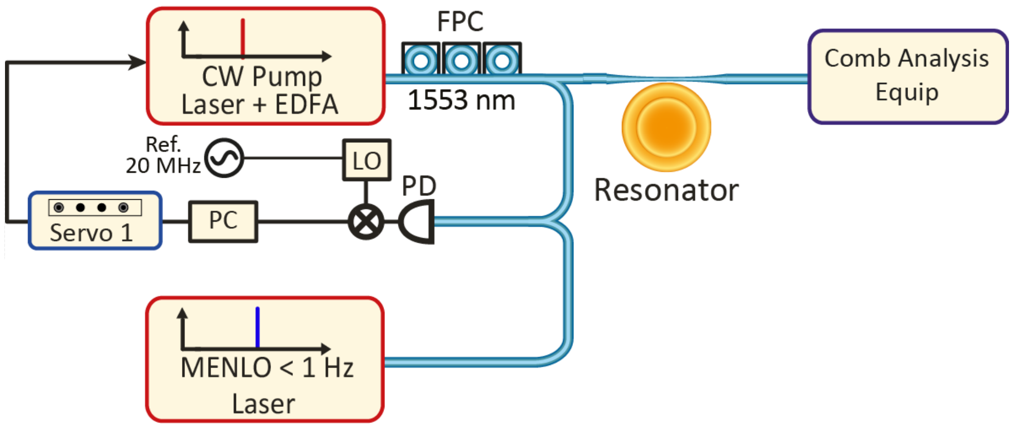
Direct generation of microwaves





Microwave Generatoin Using Dissipative Kerr Cavity Solitons

- Convert ultra stable laser to stable micro-waves
- Direct generation of low noise microwaves

J. Jost et al., **unpublished (collaboration Menlo GmbH, DARPA PULSE)**

Generation of low noise Microwaves using a Soliton State

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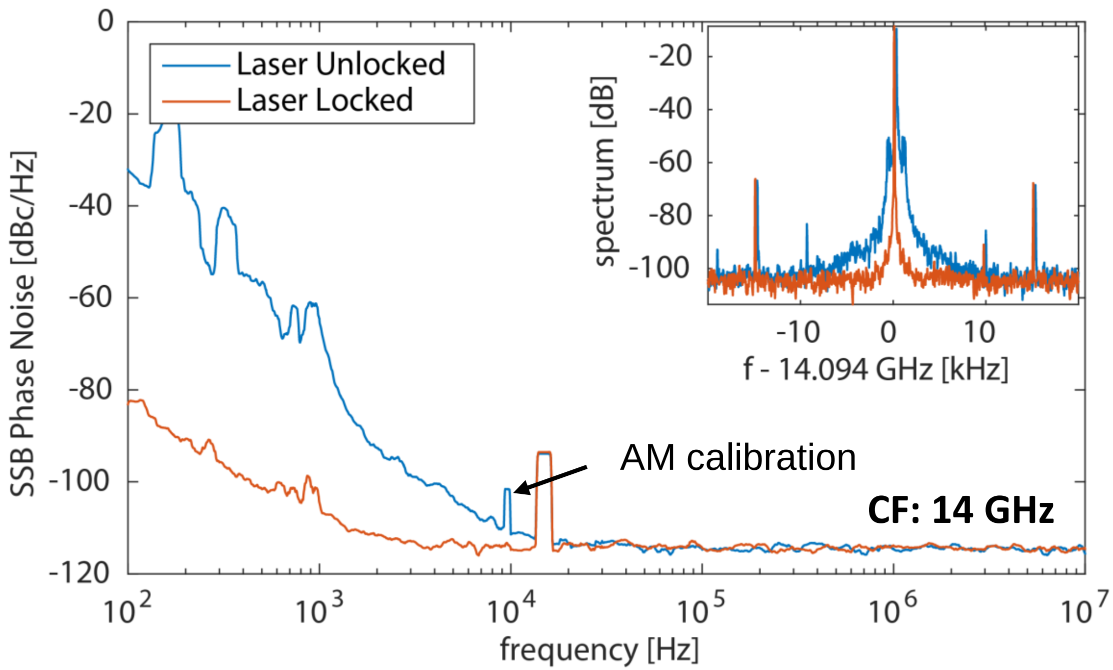
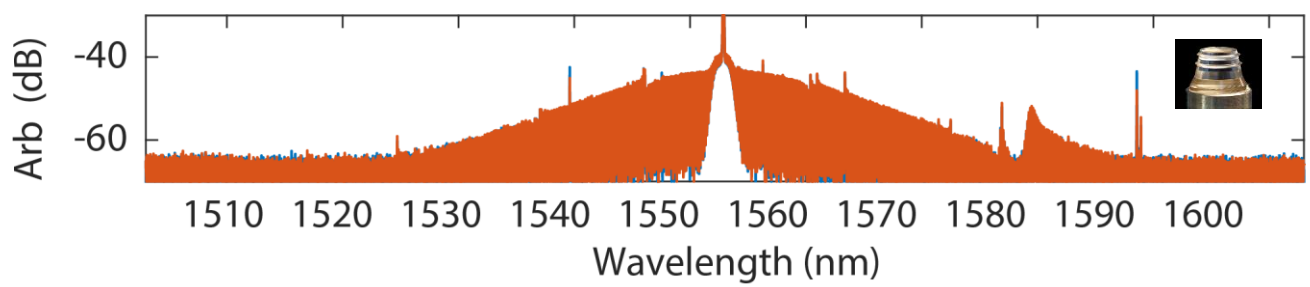
- Low noise laser allows us to significantly reduce pump phase noise

Phase Noise





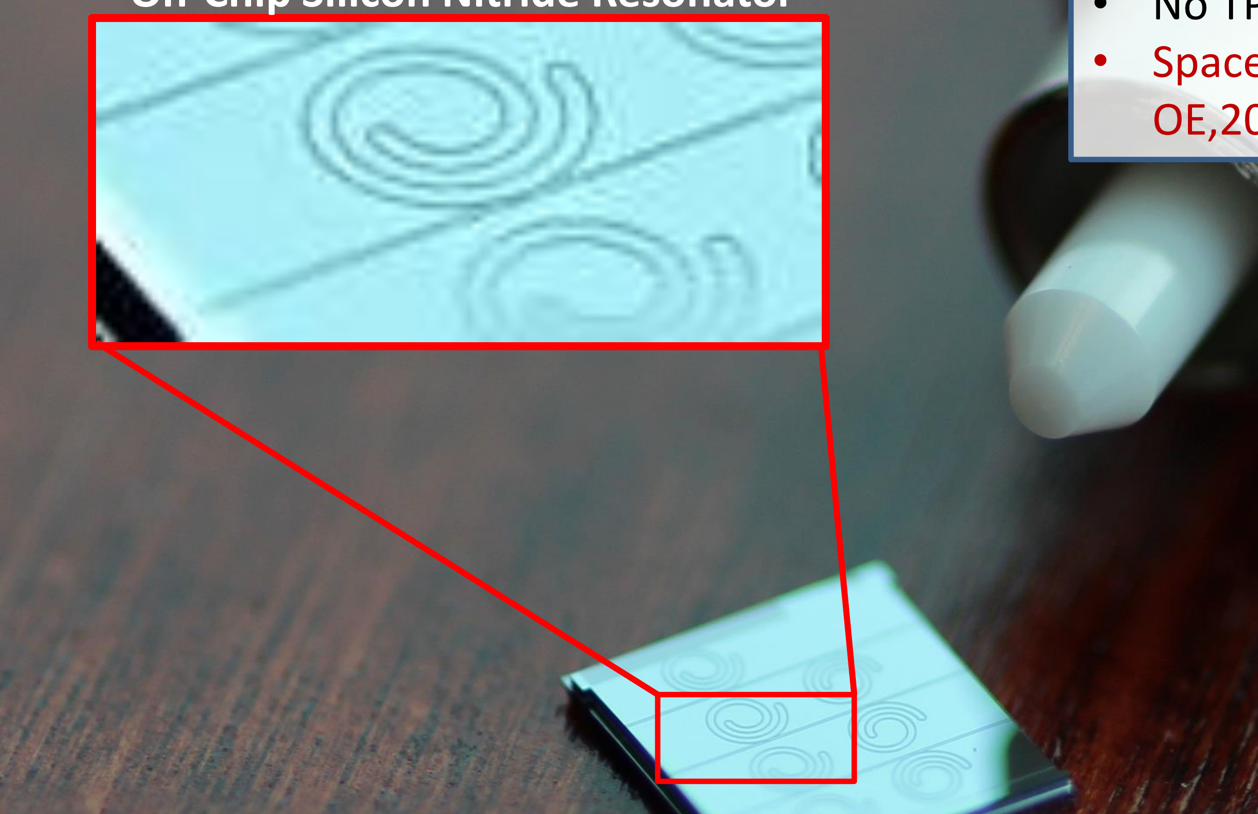
J. Jost et al., **unpublished (collaboration Menlo GmbH, DARPA PULSE)**

Soliton formation in microresonators

Silicon Nitride photonic chips

- Planar geometry
- Transparency from visible to MIR
- High effective nonlinearity
- No TPA
- Space compatible Material (Brasch, OE,2013)

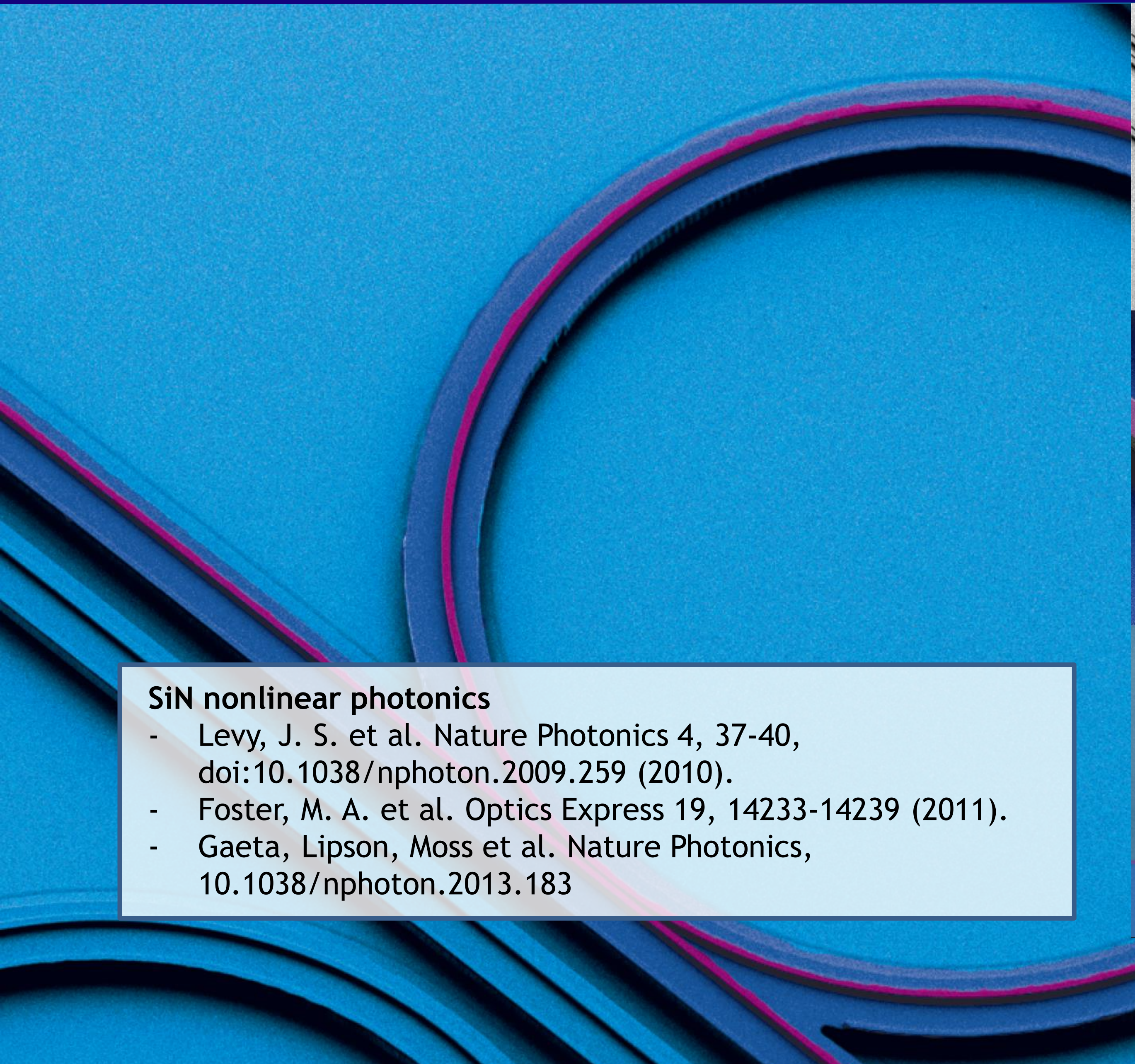
On-Chip Silicon Nitride Resonator



Crystalline Magnesium Fluoride Resonator

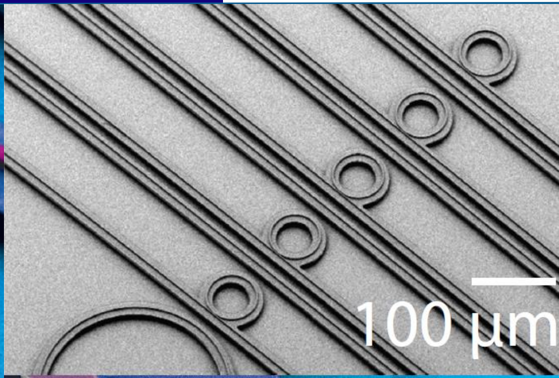
Review: D. J. Moss, R. Morandotti, A. L. Gaeta, and M. Lipson, Nature Photonics 7, 597-607 (2013)
Foster, J. S. Levy, O. Kuzucu, K. Saha, M. Lipson, and A. L. Gaeta, Opt. Express 19, 14233-14239 (2011).

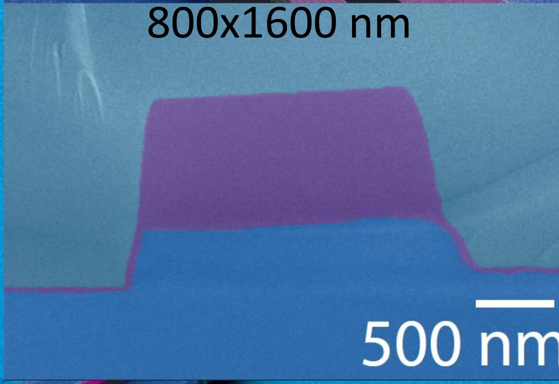
SiN microresonators



SiN nonlinear photonics

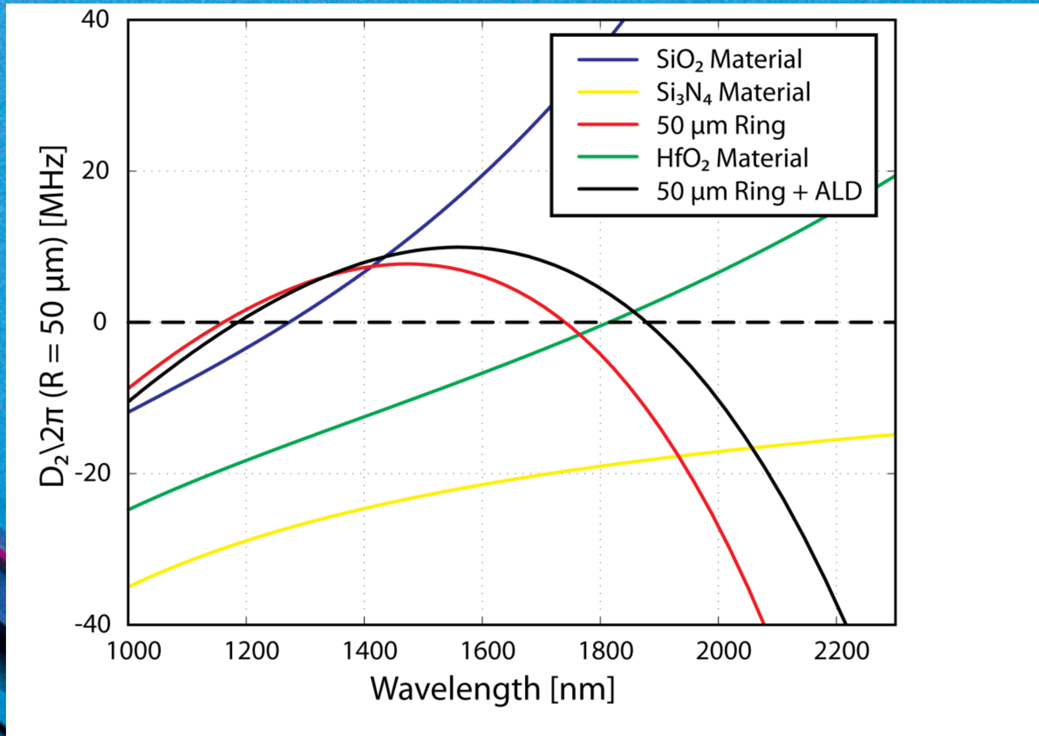
- Levy, J. S. et al. Nature Photonics 4, 37-40, doi:10.1038/nphoton.2009.259 (2010).
- Foster, M. A. et al. Optics Express 19, 14233-14239 (2011).
- Gaeta, Lipson, Moss et al. Nature Photonics, 10.1038/nphoton.2013.183

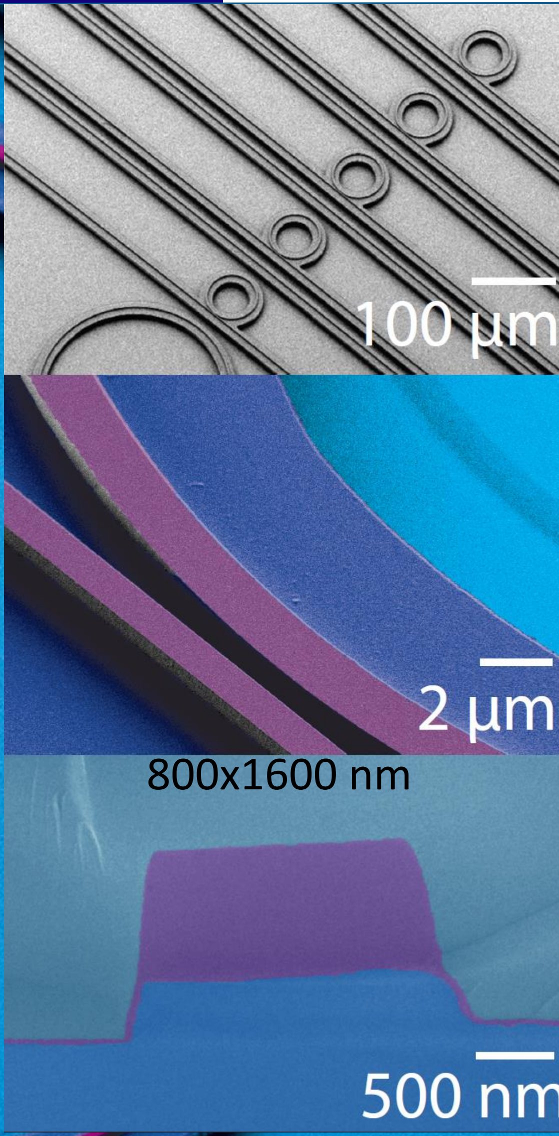




- J. Riemensberger, Optics Express 2012

Dispersion optimized SiN microresonators





SiN nonlinear photonics

- Levy, J. S. et al. Nature Photonics 4, 37-40, doi:10.1038/nphoton.2009.259 (2010).
- Foster, M. A. et al. Optics Express 19, 14233-14239 (2011).
- Gaeta, Lipson, Moss et al. Nature Photonics, 10.1038/nphoton.2013.183

- J. Riemensberger, Optics Express 2012

Soliton Cherenkov Radiation (Theory)

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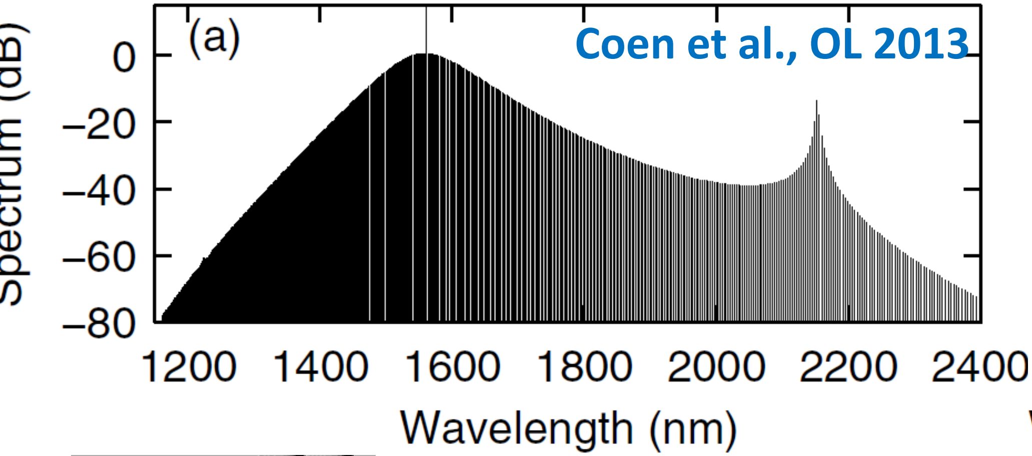
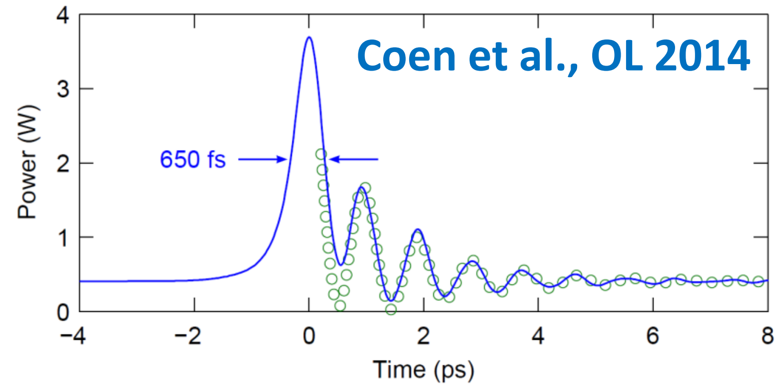
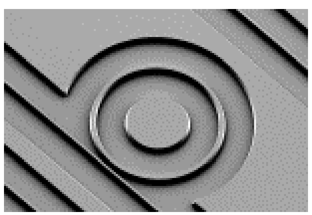
Optical spectrum



Time domain waveform





Cherenkov radiation emitted by solitons in optical fibers

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(Received 15 April 1994)

$$u^{0}_{\mathrm{sol}}(x,t) = A\,\mathrm{sech}(At)\exp[ik_{\mathrm{sol}}z]$$

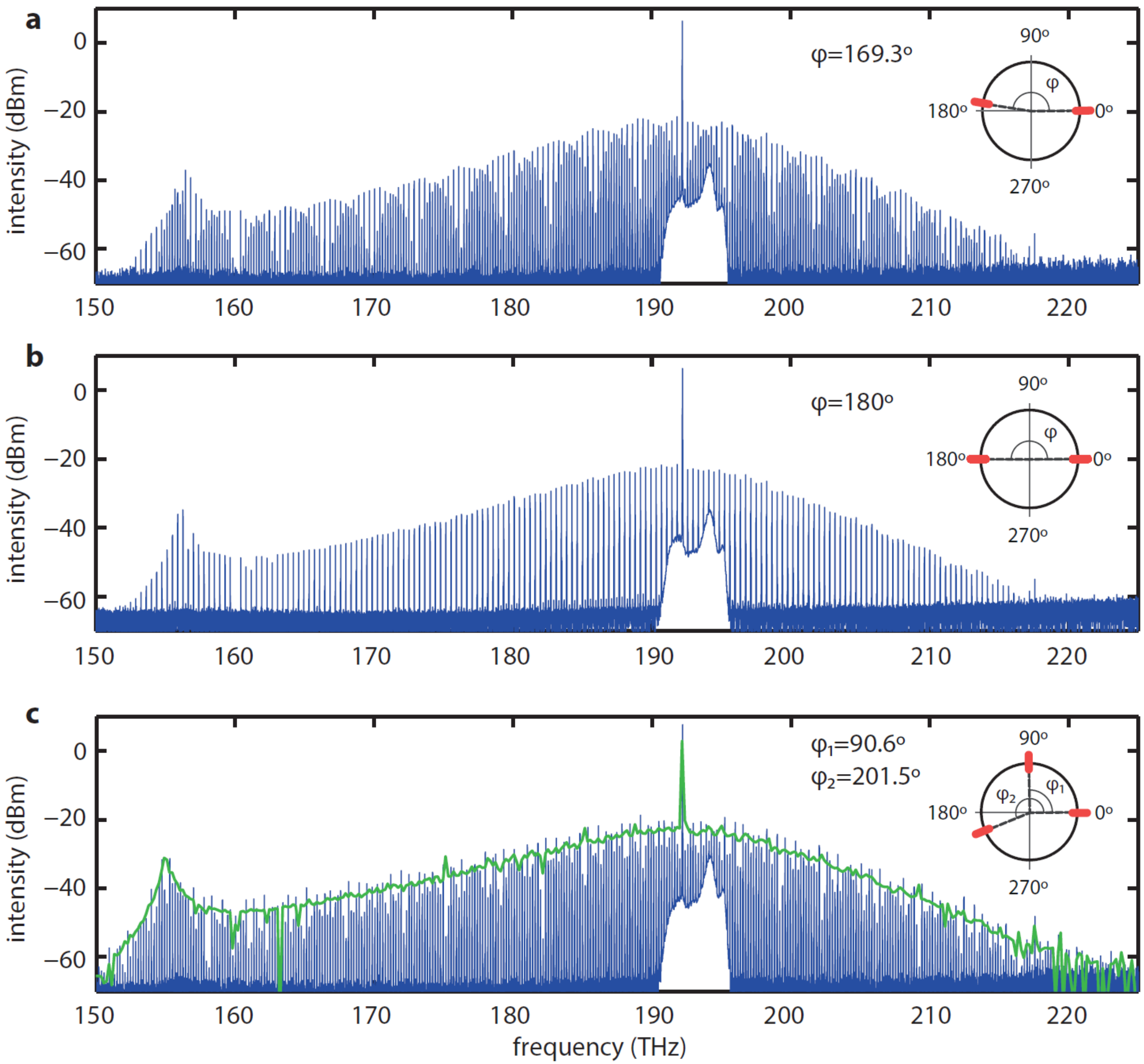
$$u^{3OD}_{\mathrm{sol}}(x,t) = A\,\mathrm{sech}(Ay) \times \exp\{ik_{\mathrm{sol}}z + i\varepsilon[2A^{2}t - 3\tanh(AY)]\}$$

Numeric modeling:
Chembo et al., OL 2010
Coen et al., OL 2013
Lamont et al., OL 2013
...

Soliton induced Cherenkov radiation

- "Supercontinuum generation in photonic crystall fiber" Dudley, Coen, Rev. Mod. Phys. 2006
- "Colloquium: Looking at a soliton through the prism of optical supercontinuum", Skryabin, Gorbach, Rev. Mod. Phys. 2010

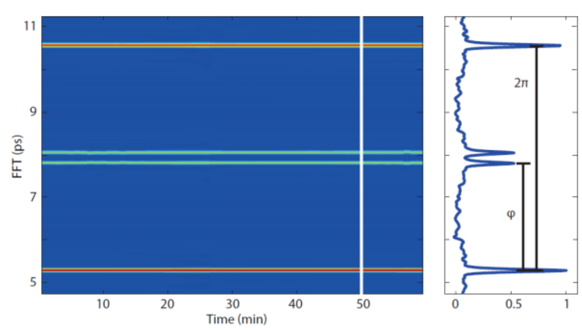
Stable multi soliton states in SiN



Reconstruction of multi soliton states in SiN

$$I(\mu) = \left| \sum_{j=1}^{N} \exp(i\phi_j \mu) \right|^2$$

Stability measurements



V.Brasch, et al. **arXiv:1410.8598** (2014)

Generation of a single soliton in a SiN resonator

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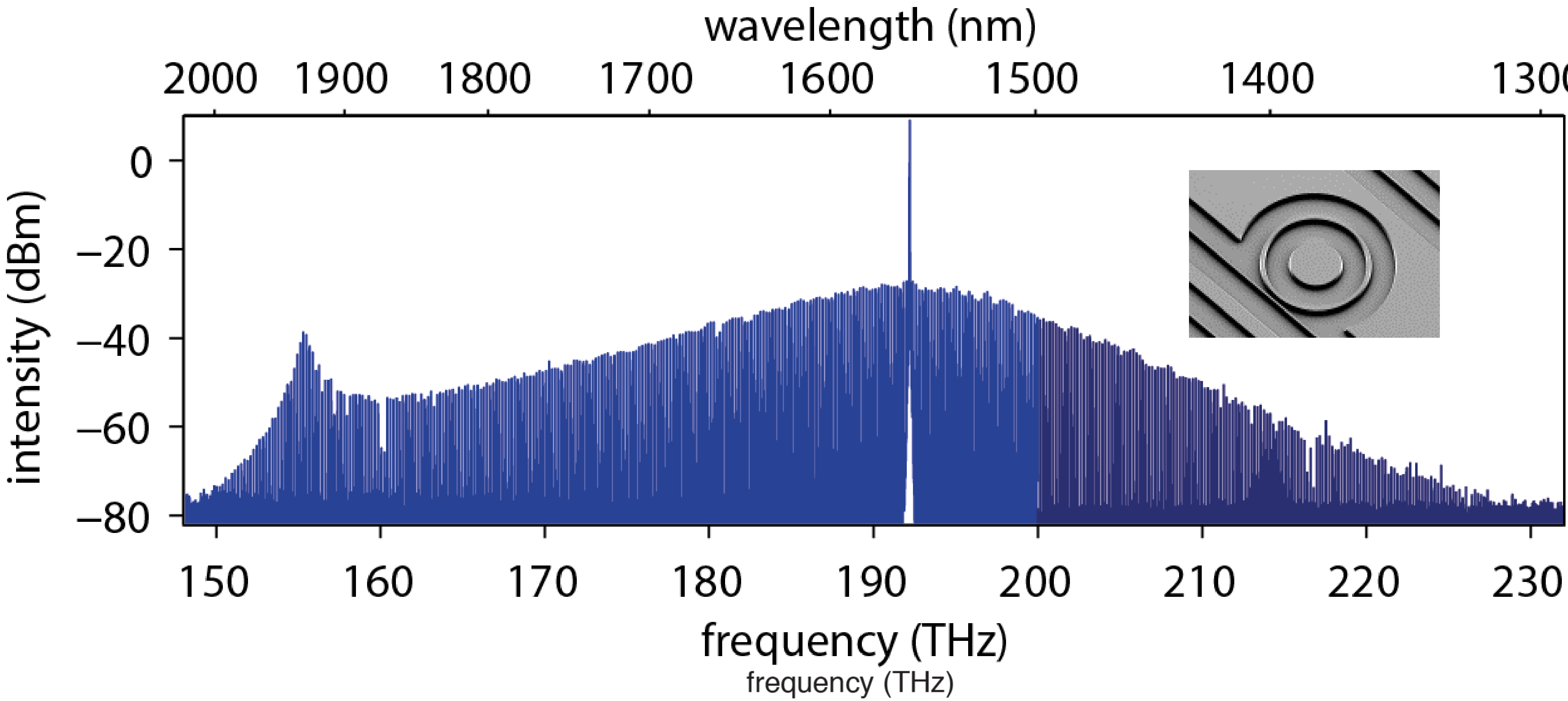
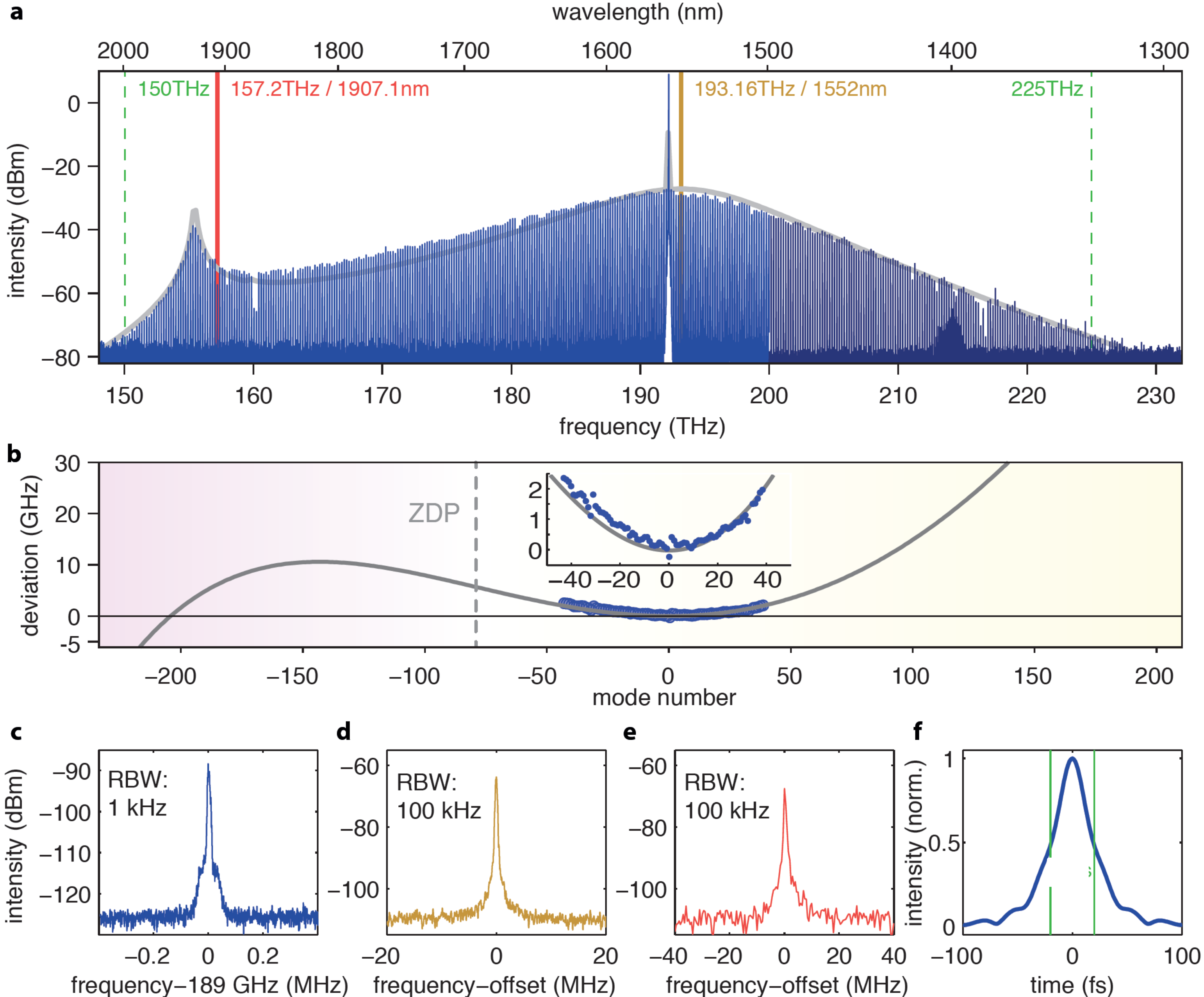


- Single temporal soliton state
- Spectrum is exceeding 2/3 of an octave
- More than 500 comb lines covering 75 THz
- Corresponds to a <25 fs pulse (5 cycles)

Note: there is **no** soliton recoil effect

V.Brasch, et al. **arXiv:1410.8598** (2014)

Modeling of the single soliton spectrum



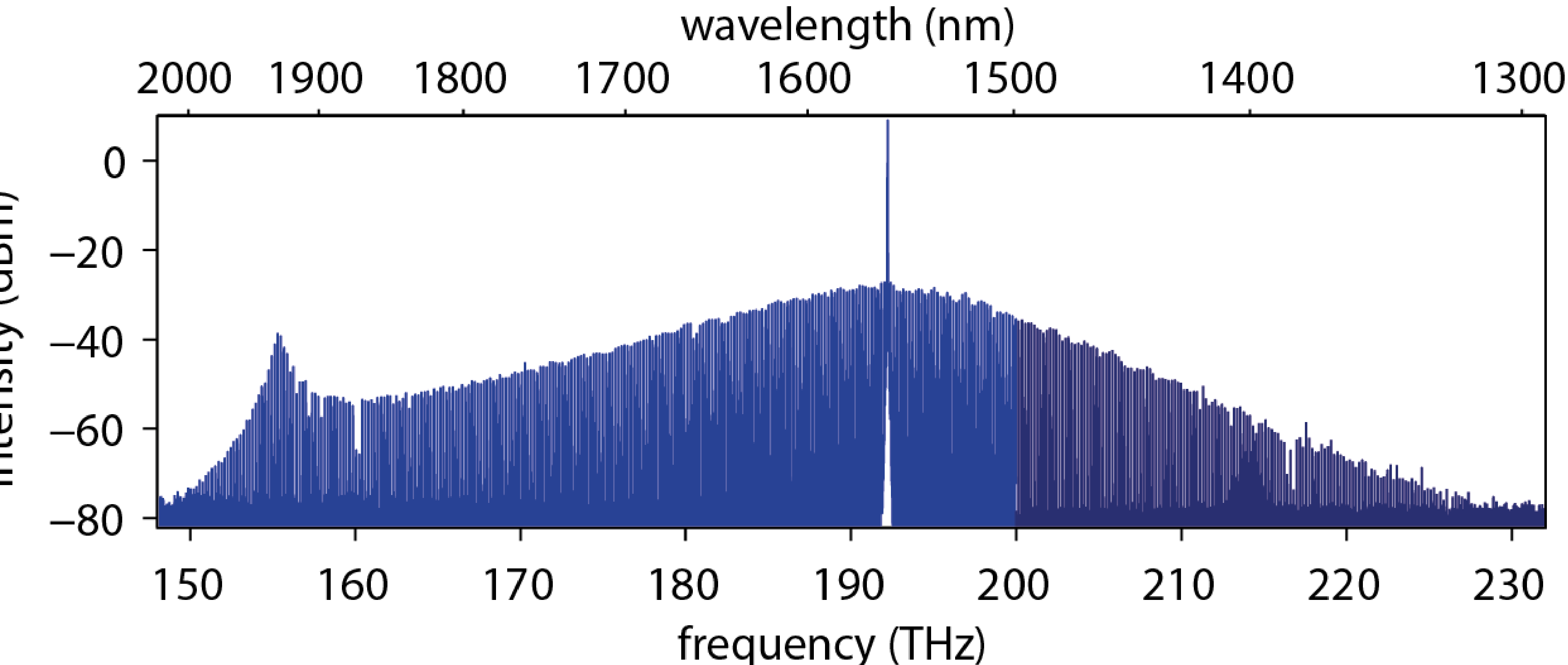
Linear model for DW:

$$\mu_{ZDP} = -\frac{D_2}{D_3}$$

$$\mu_{DW} = -3\frac{D_2}{D_3}$$

Pulse duration corresponds to <25 fs (ca. 5 optical cycles)

Soliton induced Cherenkov radiation comb

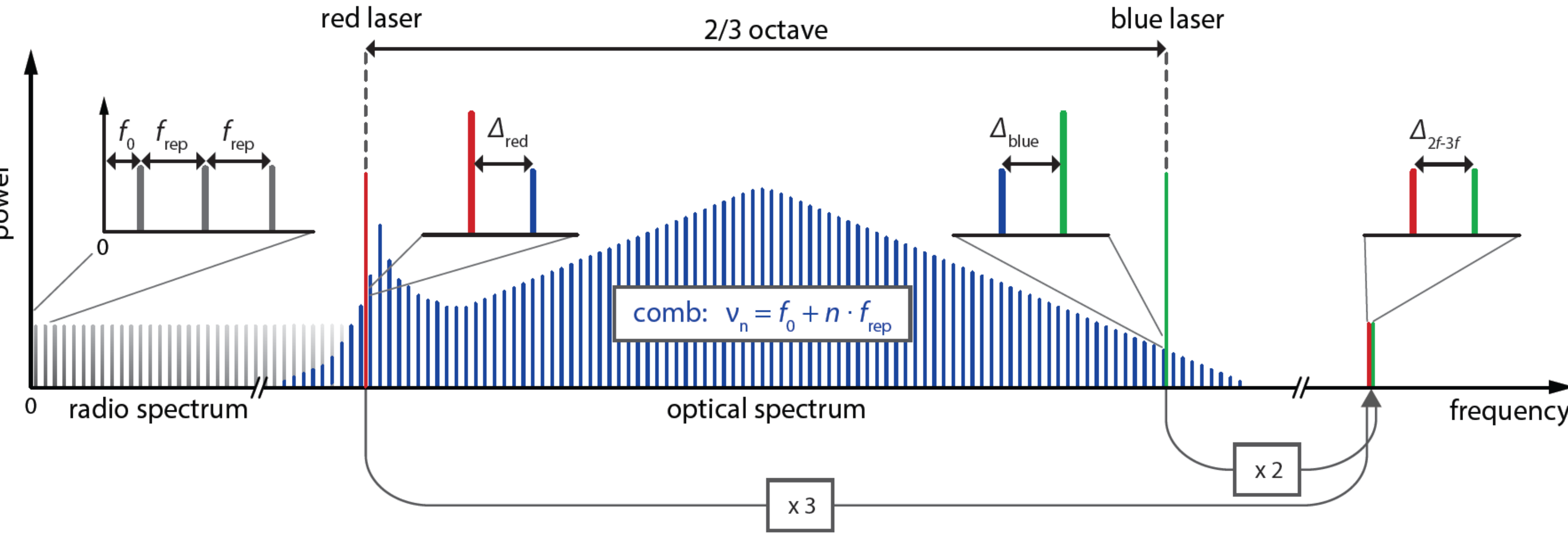


Advantages of Soliton Induced Cherenkov radiation comb:

- Coherence across the full optical spectrum
- Smooth & numerically predictable spectral envelope
- Dispersive wave enhances power in the wings
- Increased spectral coverage into normal dispersion regime

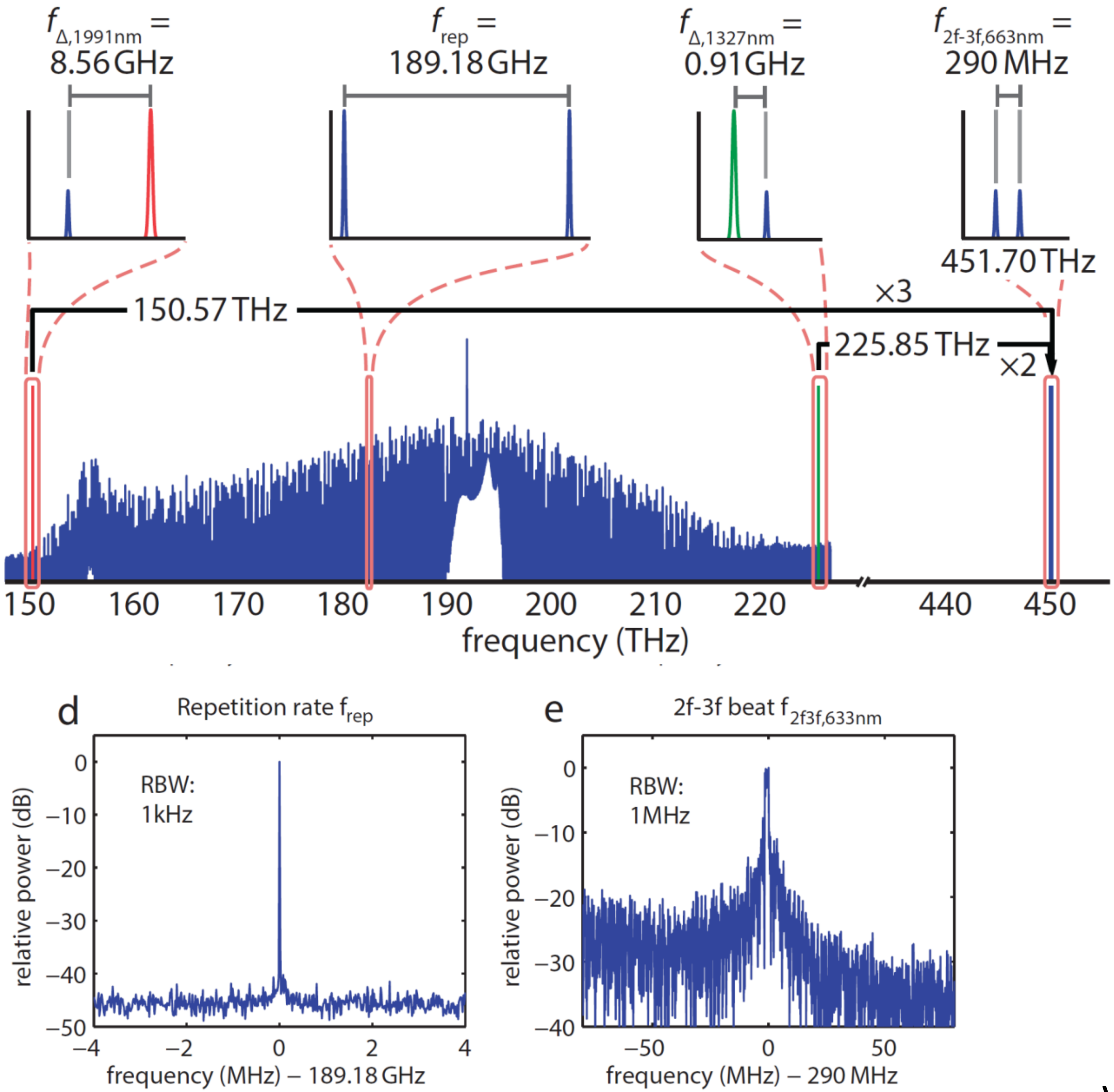
V.Brasch, et al. **arXiv:1410.8598** (2014)

2f-3f self referencing of photonic chip-frequency comb



V.Brasch, et al. **unpublished (2015)**

2f-3f self referencing of photonic chip-frequency comb



Self-referencing

- Used 2f-3f self referencing method
- 2 transfer lasers
- Detected carrier envelope frequency

V.Brasch, et al. **unpublished (2015)**

Areas of exploration and applications

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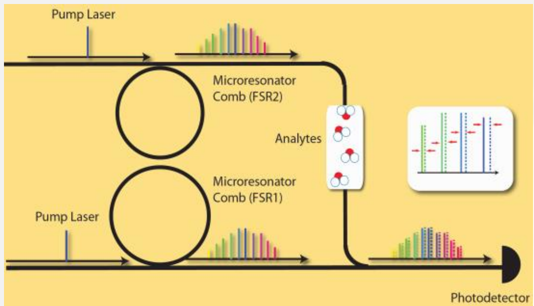
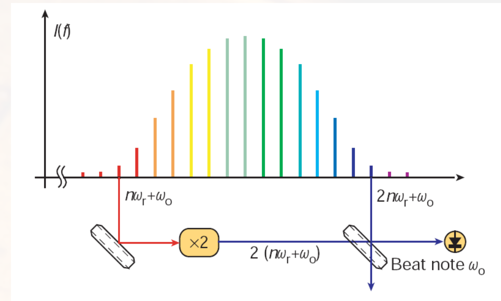
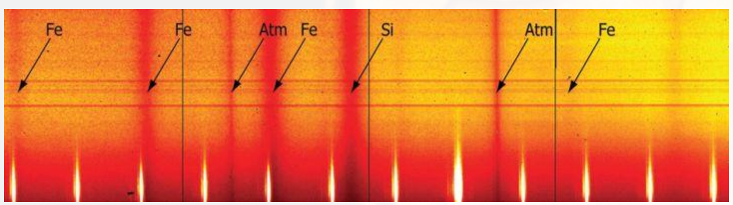
Dual comb (on chip) spectroscopy & CARS



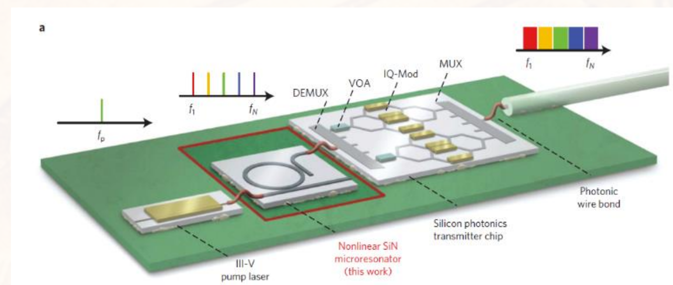
RF to Optical link on a chip *without external broadening*



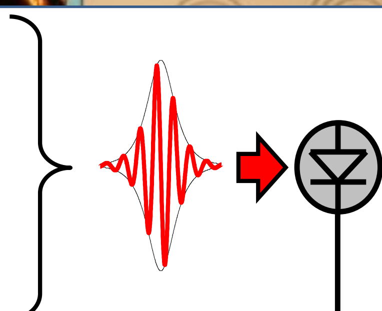
Astrophysical spectrometer calibration



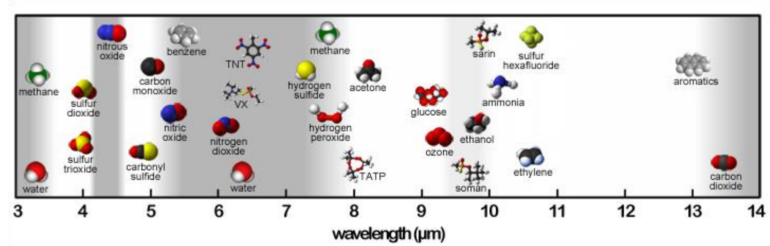
Coherent communication



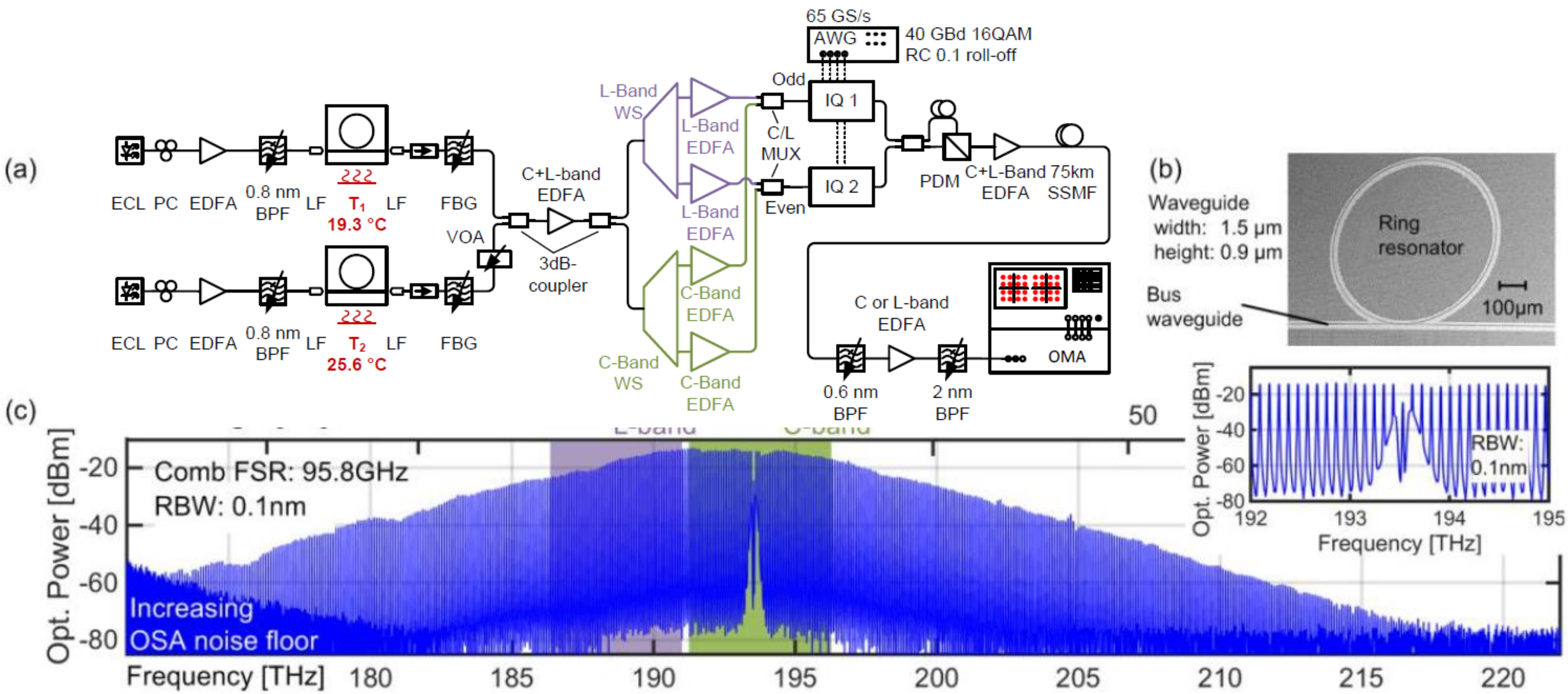
Low Noise Microwave Generation



Mid IR environmental monitoring

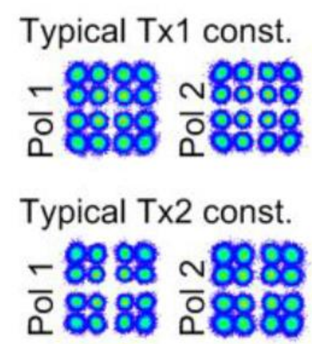


Field use: Soliton frequency combs for coherent communication*



Cavity-Soliton Kerr Frequency Comb Generation Enabling Full C and L-Band Trans. at 50 Tbit/s

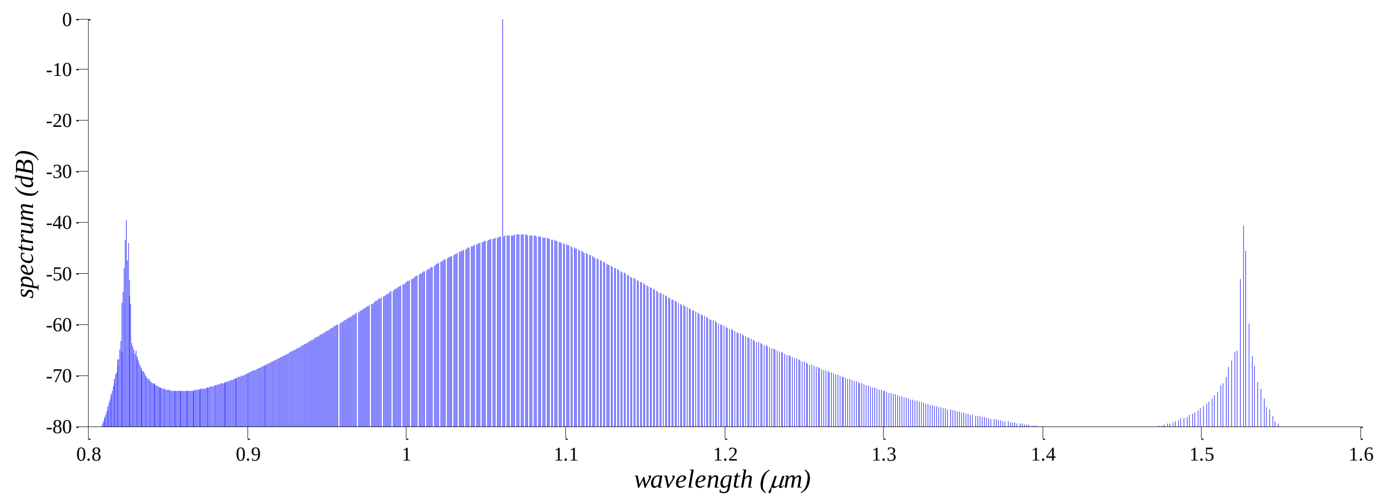
- Optical frequency comb generated by a single temporal soliton in a SiN micro-resonator for massively parallel WDM data transmission.
- 94 lines in the C and L-band to transmit 20 Tbit/s over a distance of 75 km.



*collaboration with C. Koos (KIT, Germany)

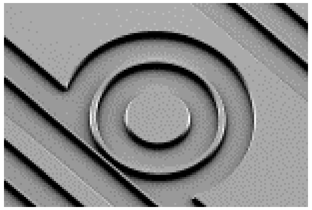
Applications in Astronomy

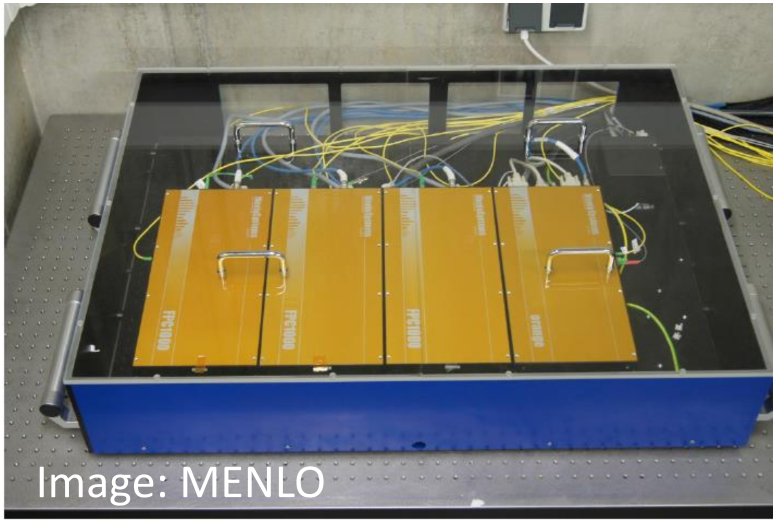
Temporal solitons at 1 micron for visible spectrometer calibration



Geometry:
Core width: 1.0 um
Core height: 0.7 um
Ring radius: ~96 um
FSR (@1 um): 250 GHz

Resonance FWHM: 150MHz
Pump: 500 mW, 1.060 um





- Replace three filter cavities with 1 micron soliton source operating at 25 GHz
- Broadening to visible carried out by PCF (Menlo Systems approach for HARPS)

Dissipative Kerr Soliton based optical frequency combs

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Present

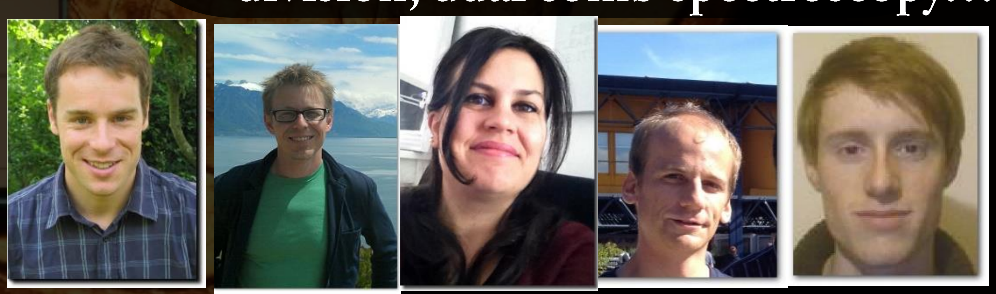
Future

Recent advances

- Soliton Cherenkov radiation on a chip
- 2/3 of Octave
- Full phase stabilization
- Mid IR extension
- Ultrashort optical pulses

Challenges of the Future

- Solitons in Visible and Mid IR spectral region
- Understand fully the Soliton Physics
- Achieve true broadband dispersion engineering
- Explore new materials
- Explore applications: astrophysical spectrometer calibration, optical division, dual comb spectroscopy….



T. Herr   J. Jost   C. Lecaplain   V. Brasch   M. Pfeiffer