Towards direct generation of wide coherent microcombs with photonic belt resonators

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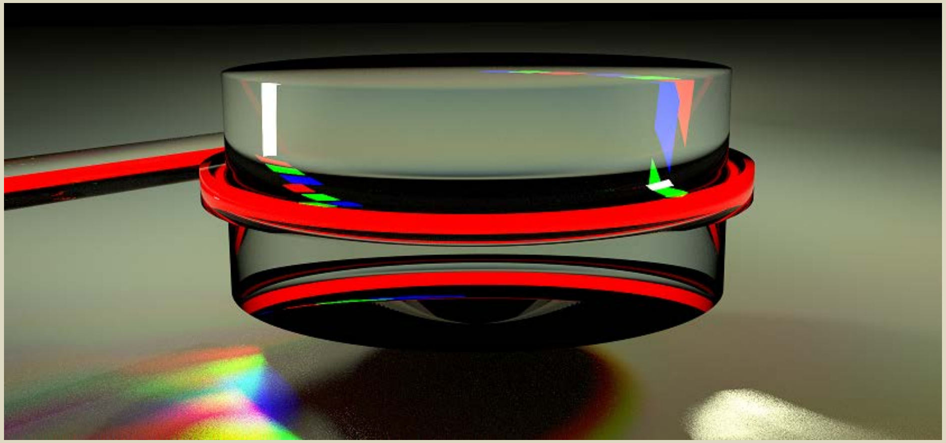

Optical frequency combs for space applications. KISS Workshop.
November 2-5, 2015

Optical frequency comb

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

- octave span for F-2F locking of f_0
- mode locking for direct measurement of f_{rep}
- f_{rep} low enough to directly measure
- Overall stability comes from external atomic clock

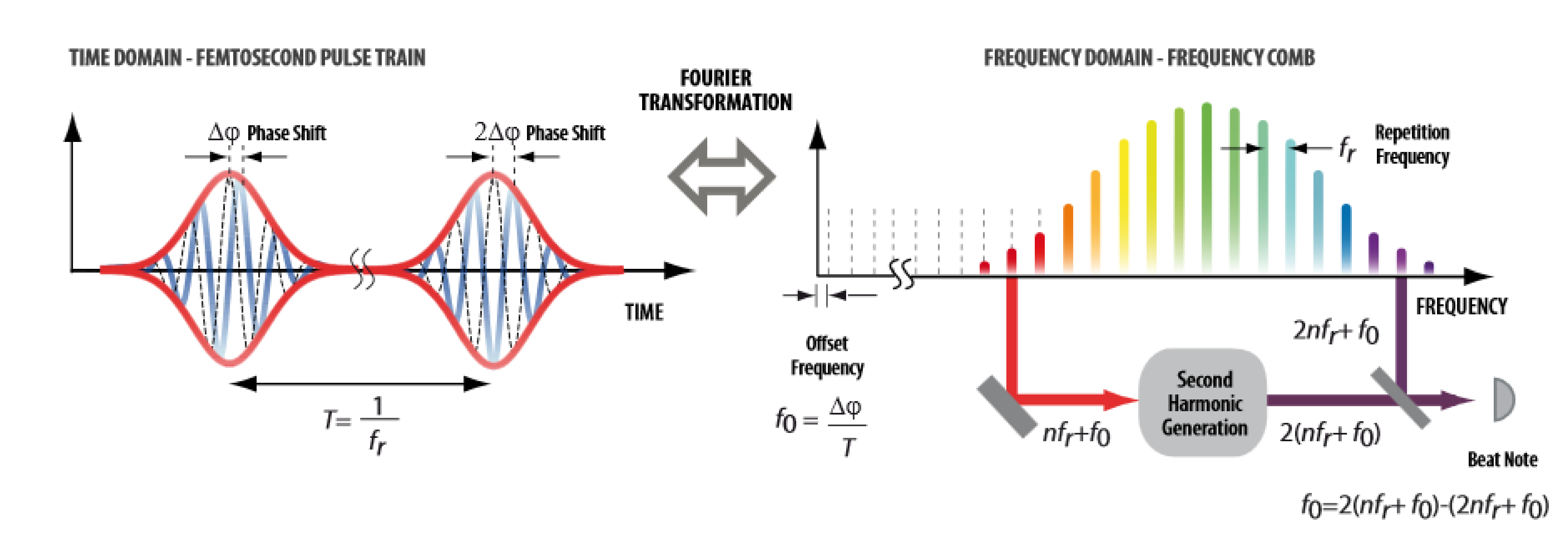

Image from: http://www.menlosystems.com

Micro-comb challenges

Can we get most of the comb features from a single microresonator?

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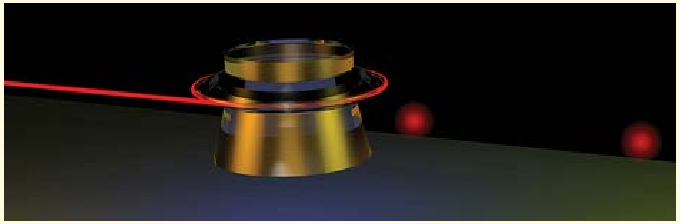
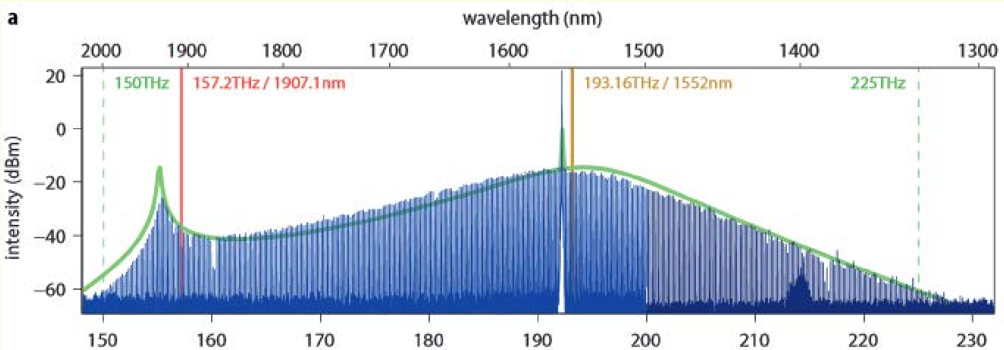


- Measurable f_{rep}
- Octave span and power sufficient for F-2F (or 2F-3F)
- Mode locked operation (solitons)

A good example of state of the art: soliton state with 2/3-octave span

There are many different platforms

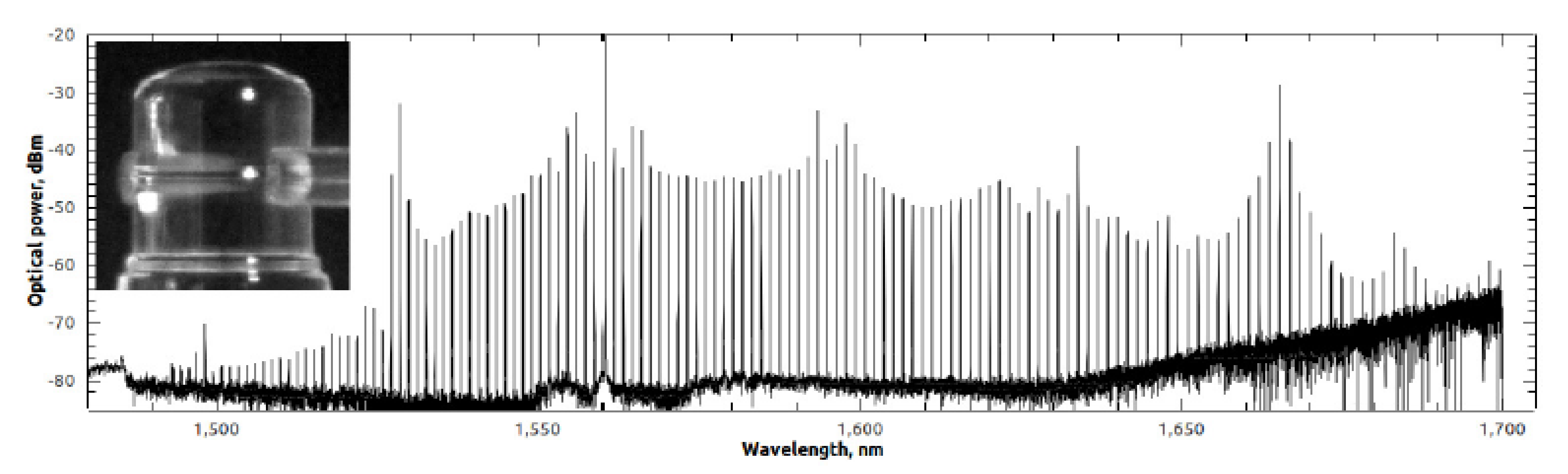


Soliton in a Si3N4 microresonator. f_{rep}=190 GHz, 2Watt pump, 2/3 octave.
http://arxiv.org/pdf/1410.8598.pdf EPFL+Skoltech

Images from k-lab.epfl.ch and http://www.menlosystems.com

Crystalline WGM resonators

Record optical (up to Q >10^{11}) and compact mode volume lead to efficient comb generation



Frequency comb observed in a resonator with engineered spectrum. The $TE_{1101,1101,1}$mode near 1560.3 nm (loaded $Q = 8.4 \times 10^7$, intrinsic $Q = 2 \times 10^8$) was pumped. Resonator diameter is 403 µm. Strong geometric dispersion leads to overall normal resonators dispersion. Over a hundred comb lines spanning more than 200 nm (23.5 THz), limited by OSA range, are observed with only 50 mW of optical pump power.

Table 1. Parameters of Various MgF_2 Microresonator-based Frequency Combs

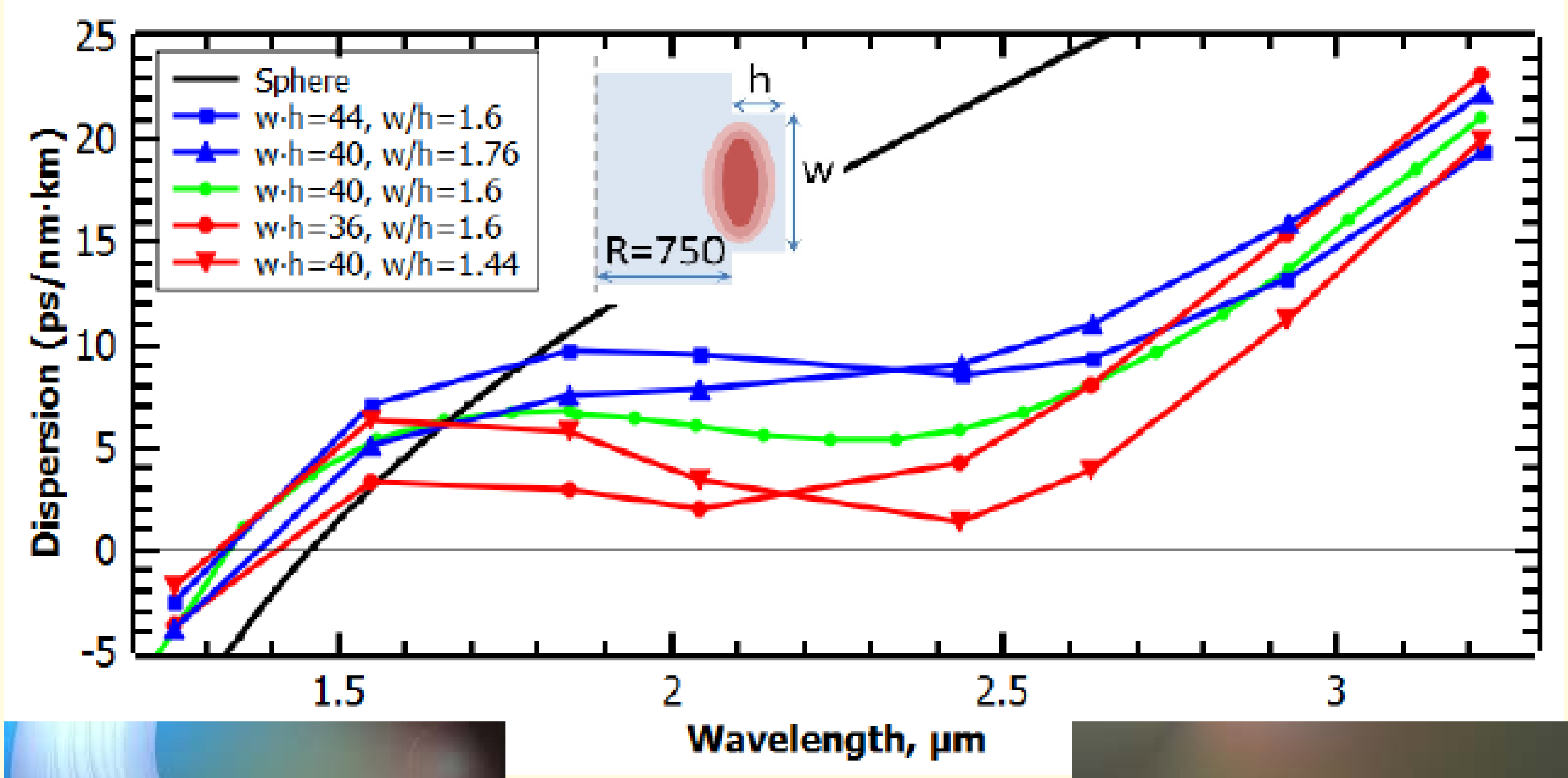
Reference	FSR, GHz (diameter, µm)	Optical Q factor near λ = 1.55 µm	Pump, mW	Pump λ, µm	Comb span, nm
[9]	107 (700)	$>10^9$	600	2.45	~200
[8]	68 (1000)	$\sim 2 \times 10^8$	500	1.56	~300
[13]	34.67 (2000)	10^9	2	1.543	~20
This work	172.44 (403)	$\sim 2 \times 10^8$	50	1.56	>200

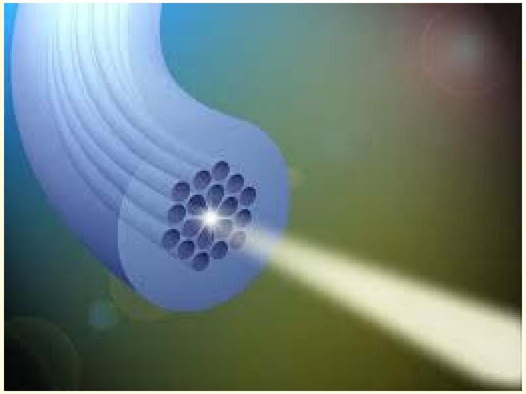
[8] T. Herr et al., “Universal dynamics of kerr frequency comb formation in microresonators,” arXiv:1111.3071.
[9] C. Y. Wang et al.,“Mid-infrared optical frequency combs based on crystalline microresonators,” arXiv:1109.2716.
[13] W. Liang et al., “Generation of nearinfrared frequency combs from a MgF2 whispering gallery mode resonator,” Opt. Lett. 36(12), 2290–2292 (2011).

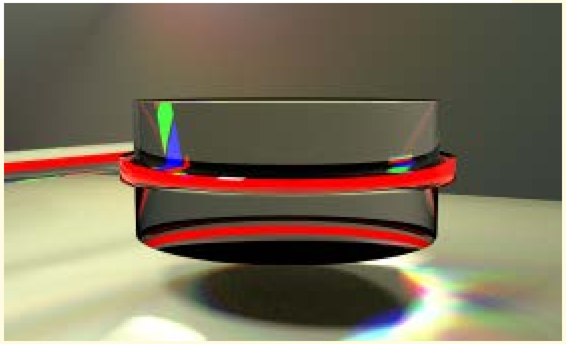
Need dispersion engineering to reach octave span

Dispersion engineering in PBR

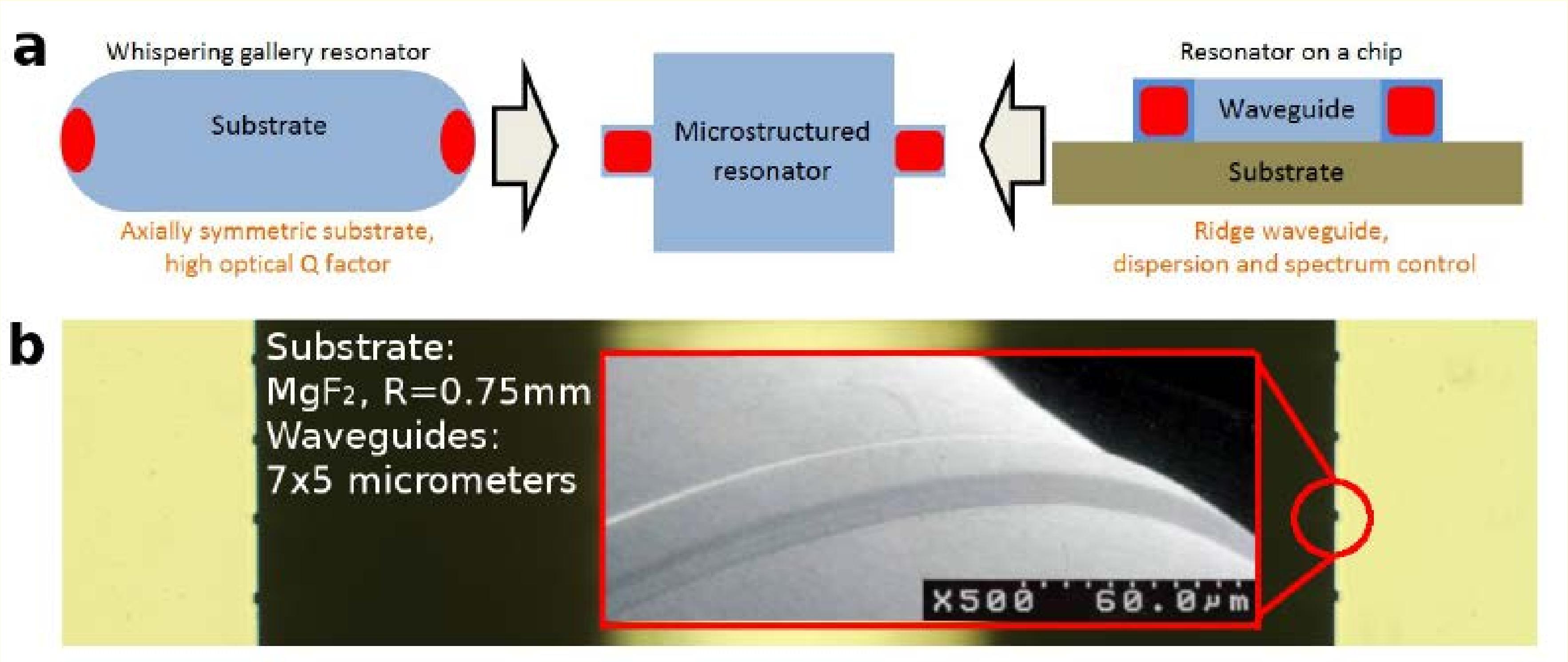
Enables dispersion engineering in crystalline WGM resonators

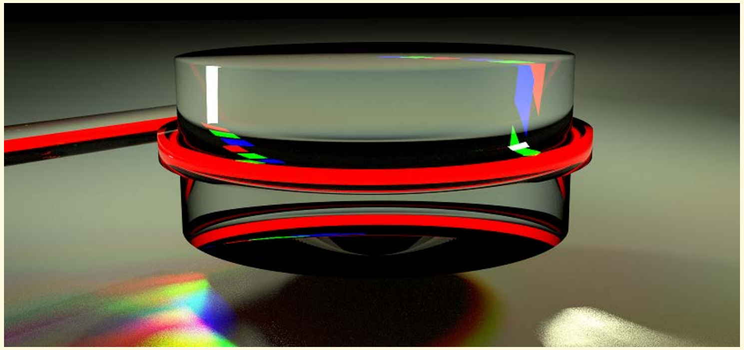




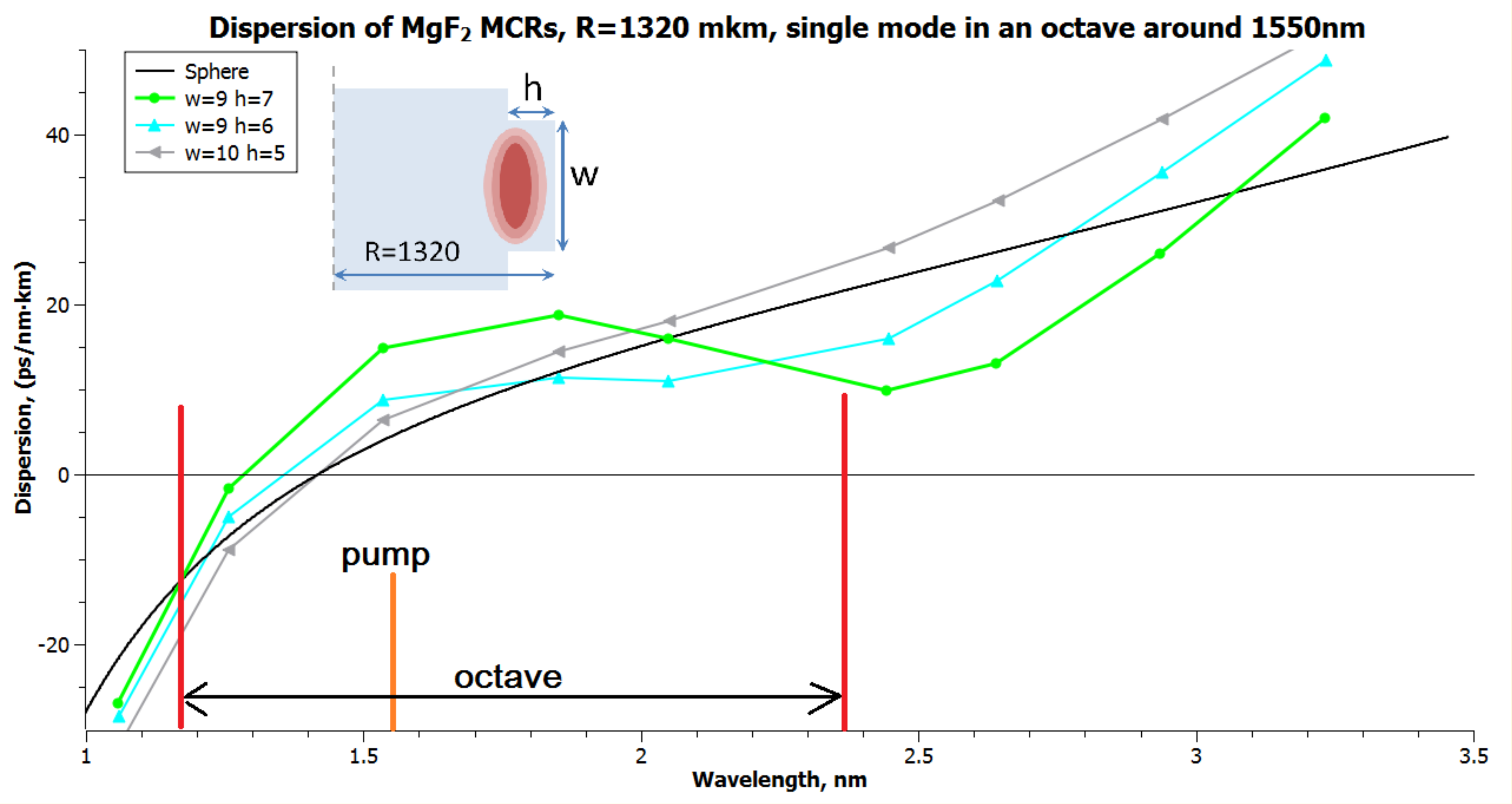


Photonic belt resonators





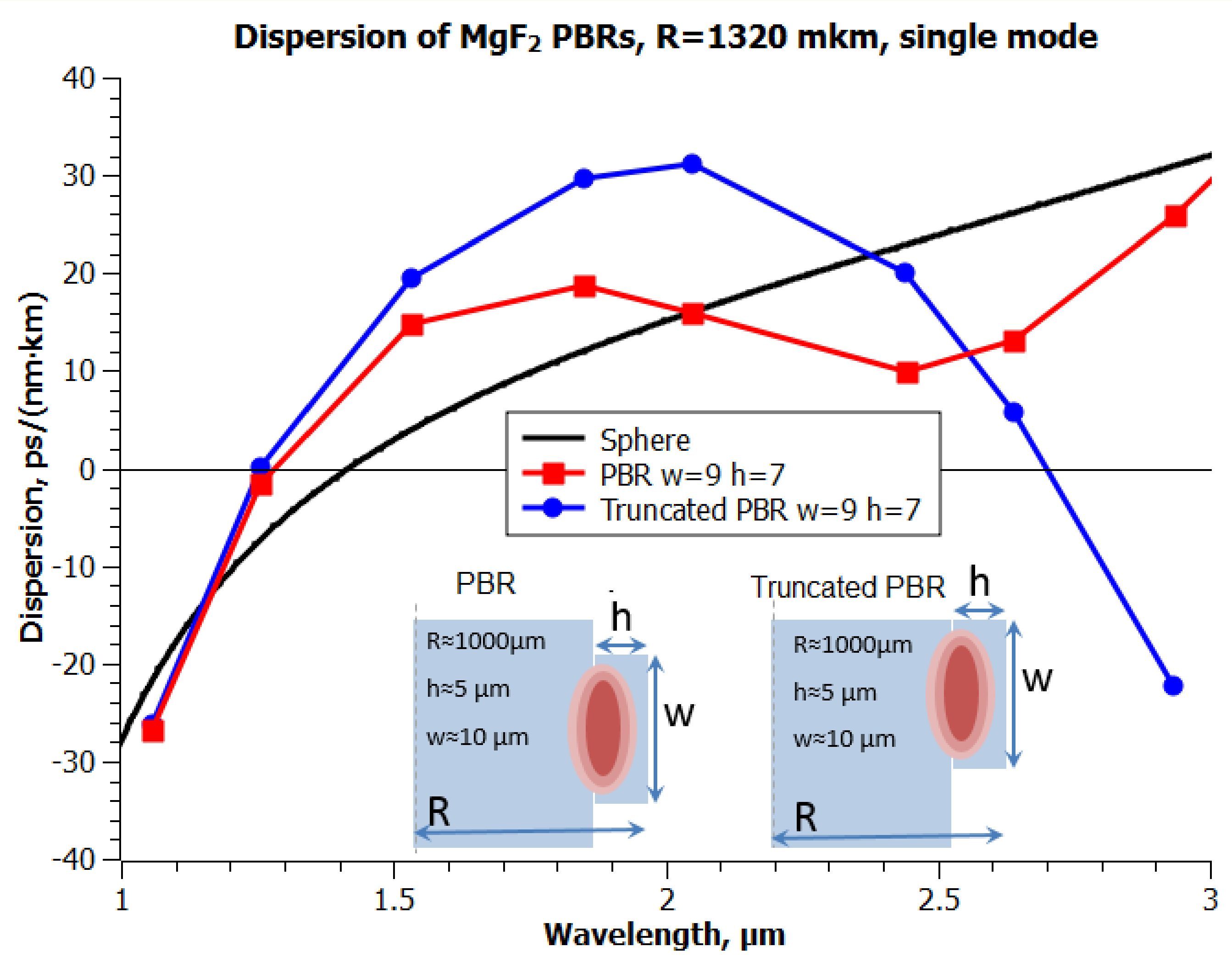
Single mode PBR in one octave



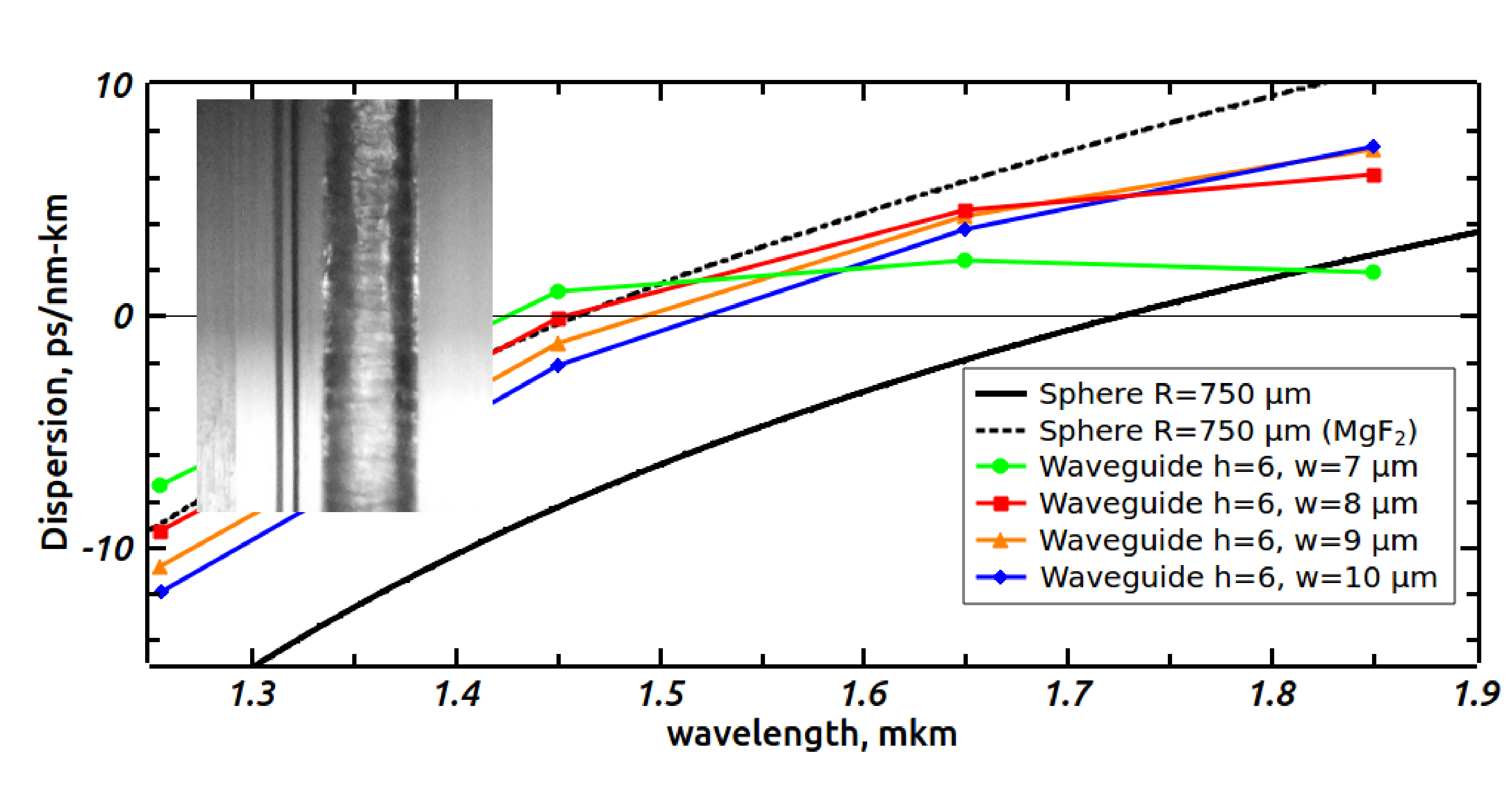
$$1 > \frac{wn}{\lambda}\sqrt{\frac{2h}{R-h}} > 0.5$$

“Morphology dependent photonic circuit elements,” A. A. Savchenkov, I. S.Grudinin, A. B. Matsko, D. Strekalov, M. Mohageg, V. S. Ilchenko, and L. Maleki. Opt. Letters 31, 1313-1315, (2006)

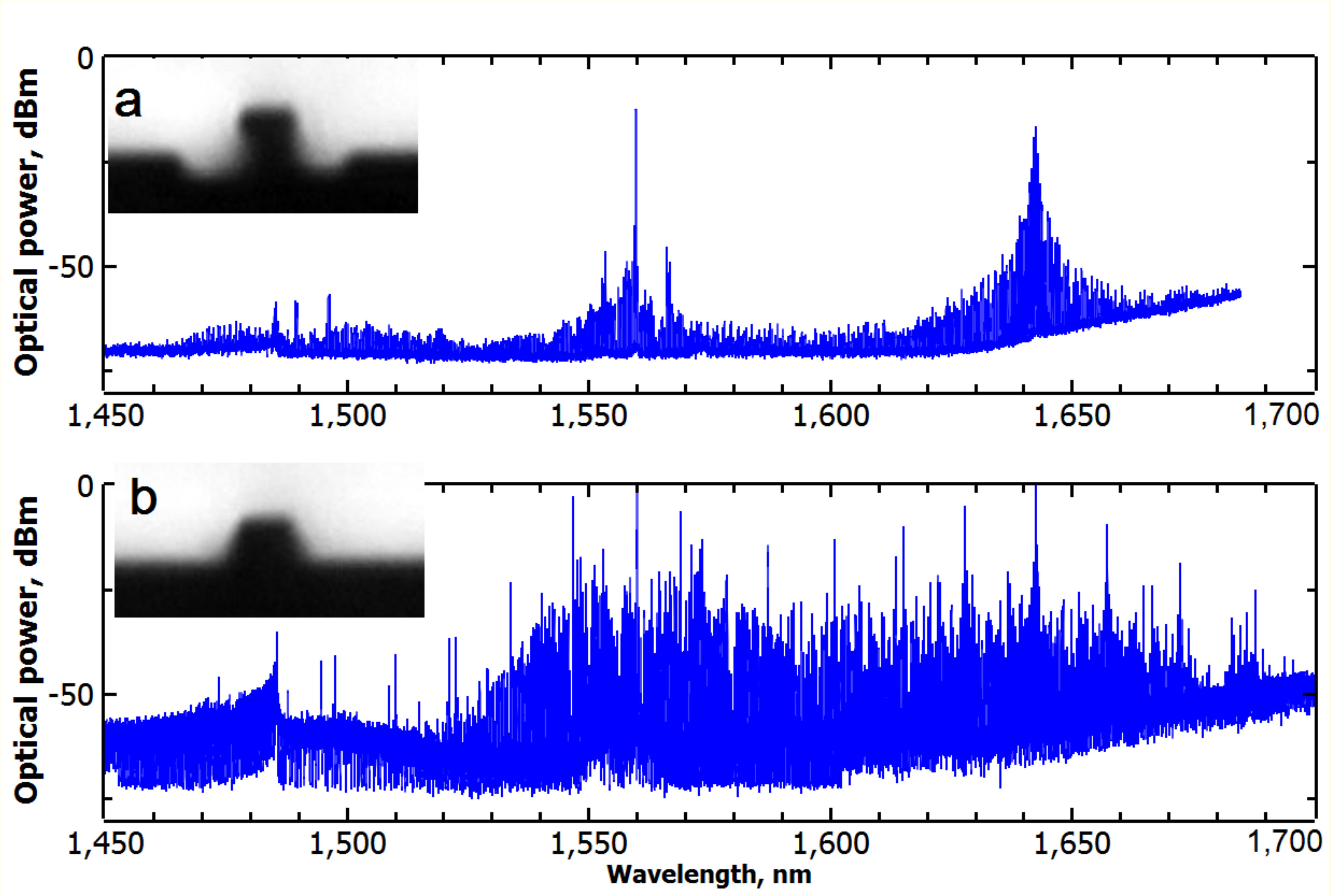
Unexplored potential of PBR



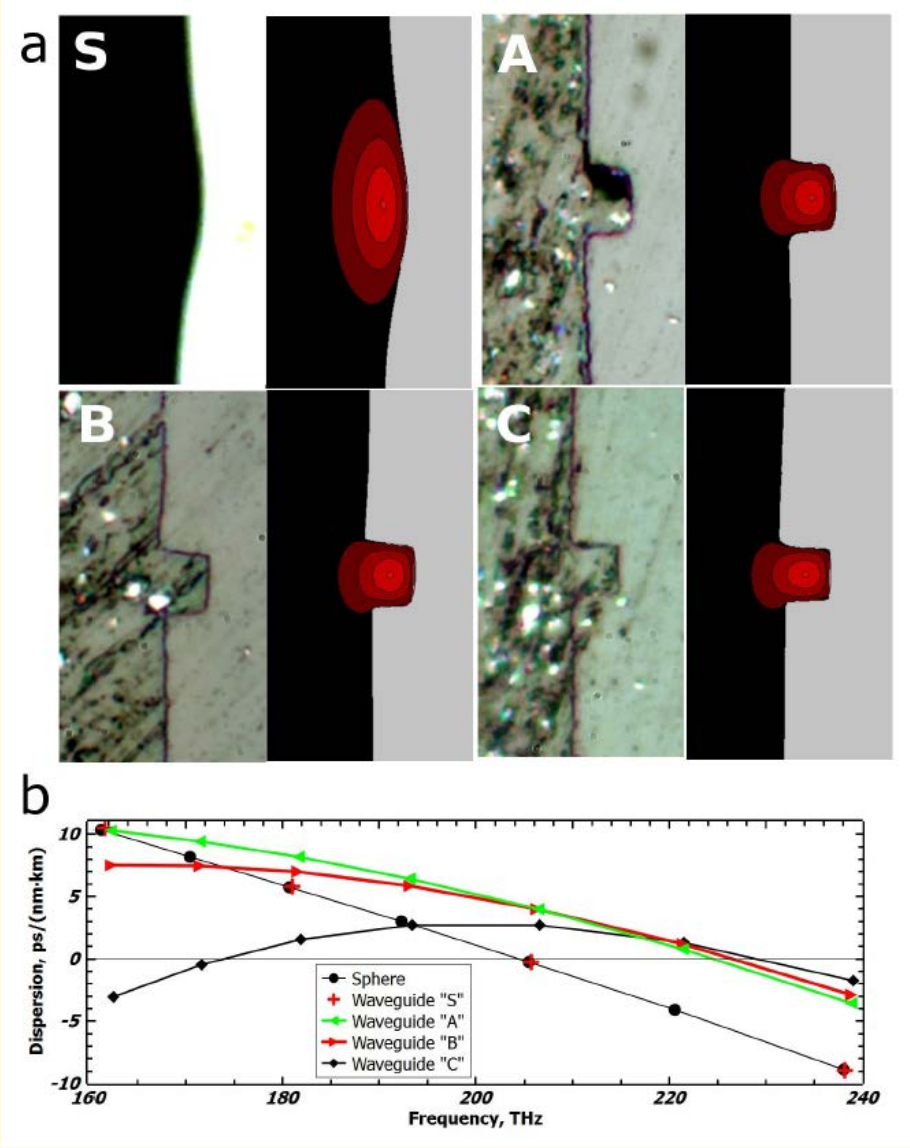
More dispersion engineering: CaF_2



More dispersion engineering: CaF_2



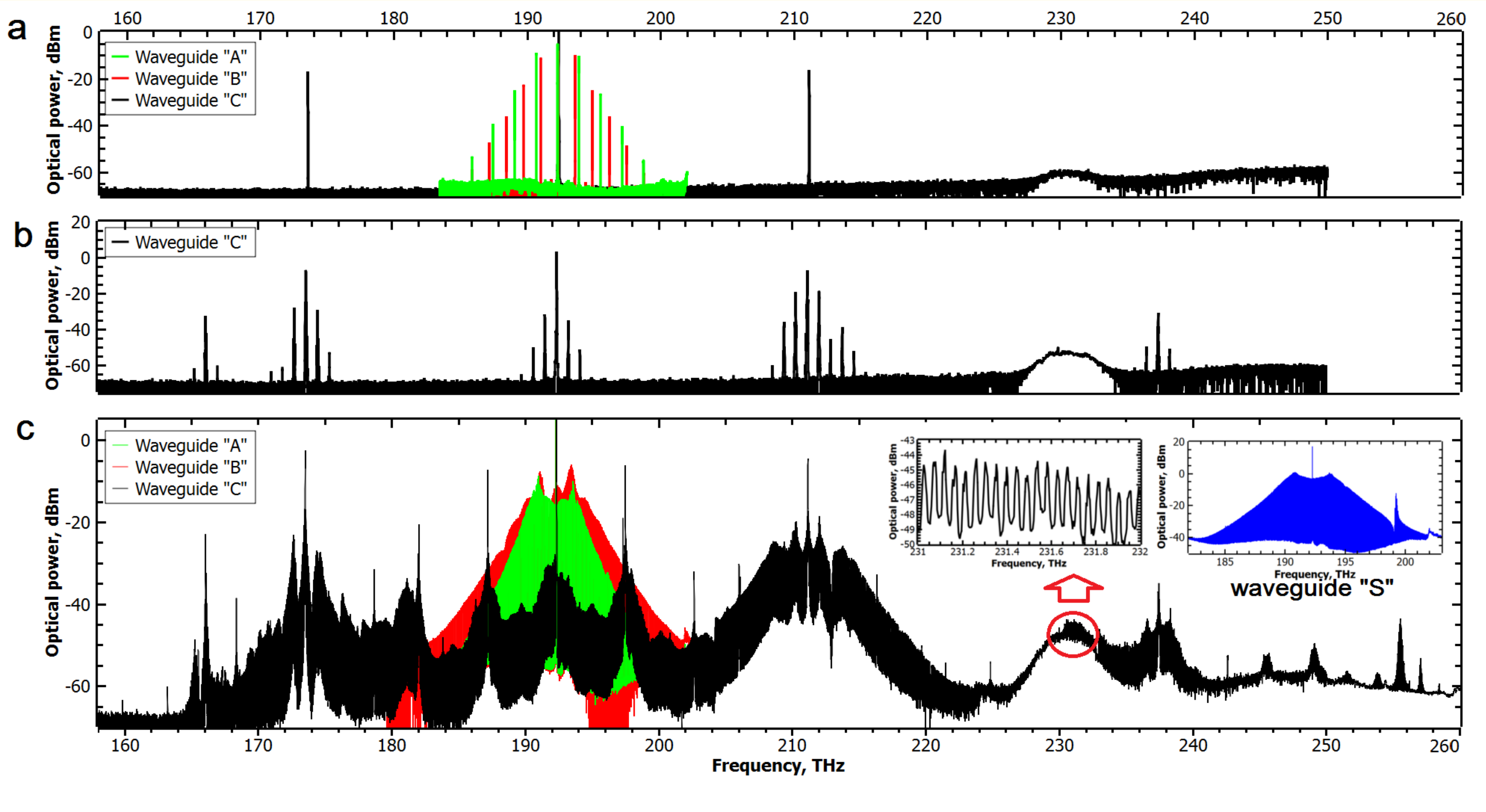
Dispersion engineering in MgF_2 PBR



Microstructured waveguides and corresponding dispersion.
a, Each of the 8 images represents an area sized 25x45 micrometers. The optical images of the waveguide cross sections are shown along with the mode intensity maps obtained with FEM modelling.
b, Numerically computed total cavity dispersion for the waveguides shown in a). The waveguide “S" with Gaussian waveguide shape, similar to previously reported single mode resonators, has the same dispersion as an ideal sphere.

I. S. Grudinin, and N. Yu, Optica **2**(3) 221-224 (2015)

PBR vs Gaussian single mode WGM



Frequency combs generated in photonic belt resonators with 300 mW of pump at λ=1560 nm (192.4 THz). a, The primary comb in waveguide ``C'' starts at N=408 in contrast to N~30 in waveguides ``A'' and ``B''. **b,** Secondary comb formation in waveguide ``C'' starts as the laser detuning is reduced. **c,** Comb states at a minimum stable detuning. The comb from the waveguide ``C'' contains nearly 2000 lines spanning 100 THz. Inset shows cavity FSR--spaced comb lines. The comb from the waveguide ``S'' shows evidence of avoided mode crossing

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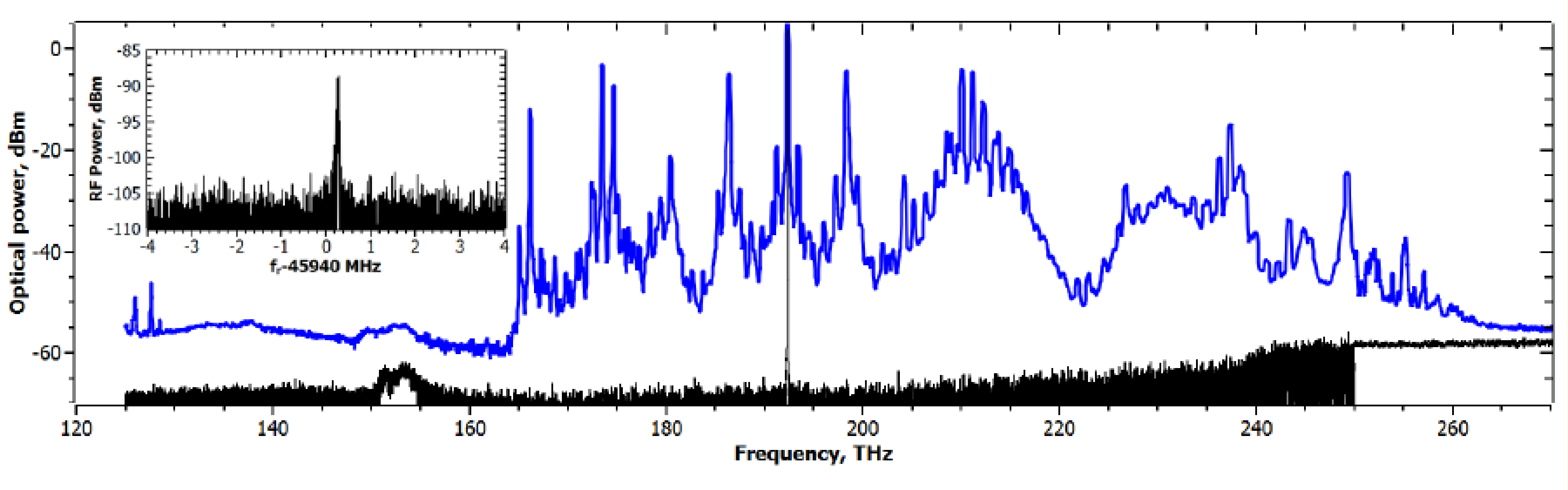
Octave spanning at 46 GHz

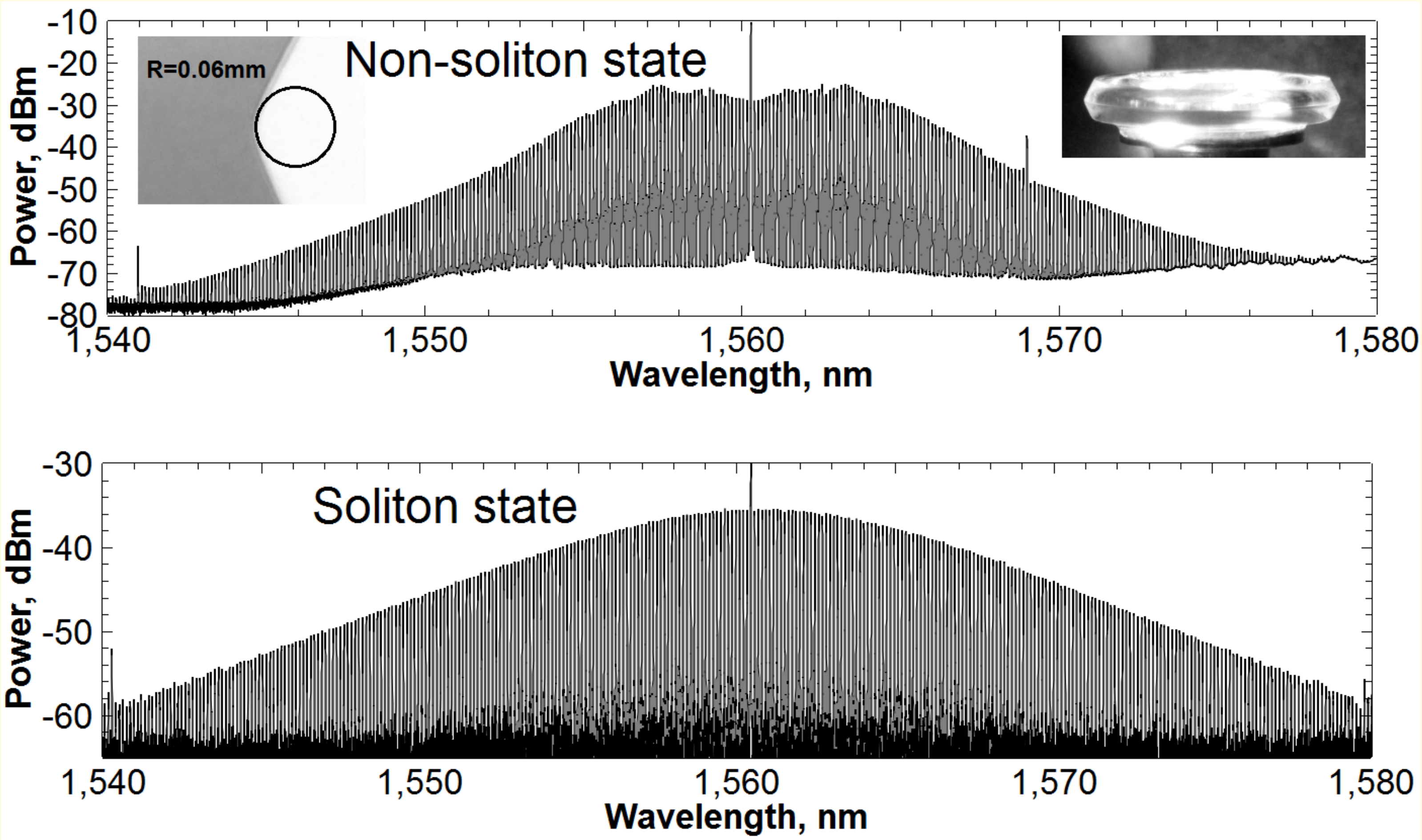
First octave spanning comb with repetition rate below 50 GHz and pump power of less than 1 W



Octave spanning frequency comb and its beatnote. Waveguide “C" produced comb lines spanning across over one octave (blue). The noise level for large laser detuning where no comb is generated is also shown (black). The gap could be explained by near-IR fiber absorption or by particular resonator dispersion and spectrum. Resonator intrinsic Q=50 million, pump power 600 mW, FSR 46 GHz.

I. S. Grudinin, and N. Yu, Optica **2**(3) 221-224 (2015)

“Frequency jump*” excitation of solitons



* "Temporal solitons in optical microresonators," T. Herr, V. Brasch, J.D. Jost, C.Y. Wang, N.M. Kondratiev, M.L. Gorodetsky, T.J. Kippenberg, Nature Photonics 8, 145-152

Spectra from: “Towards efficient octave-spanning comb with micro-structured crystalline resonator,” Ivan S. Grudinin, Nan Yu, Proc. SPIE 9343, Laser Resonators, Microresonators, and Beam Control XVII, 93430F (March 13, 2015)

MgF_2 PBR

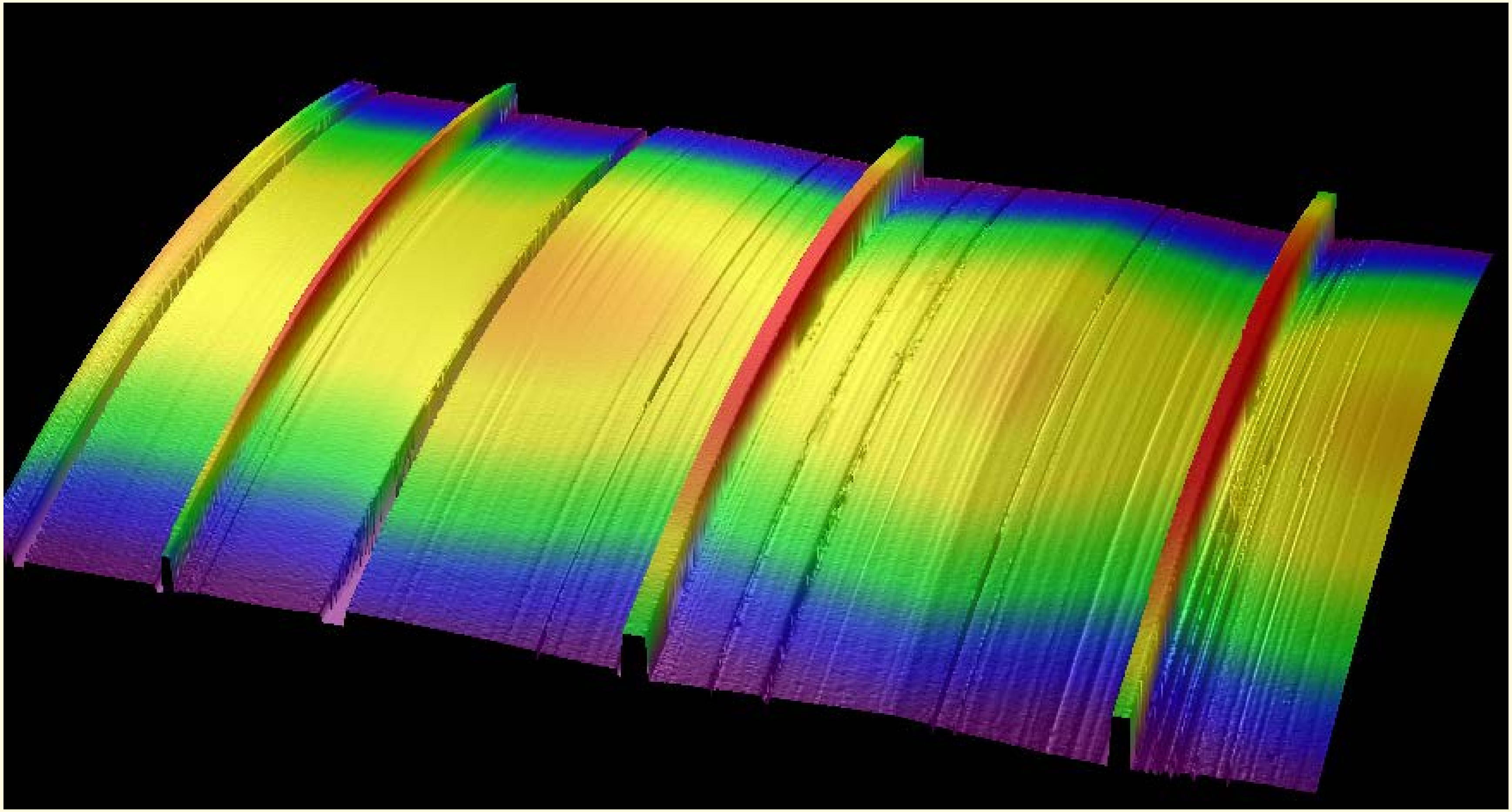
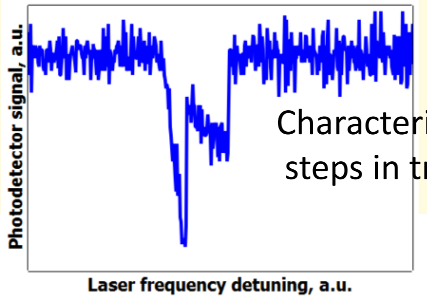


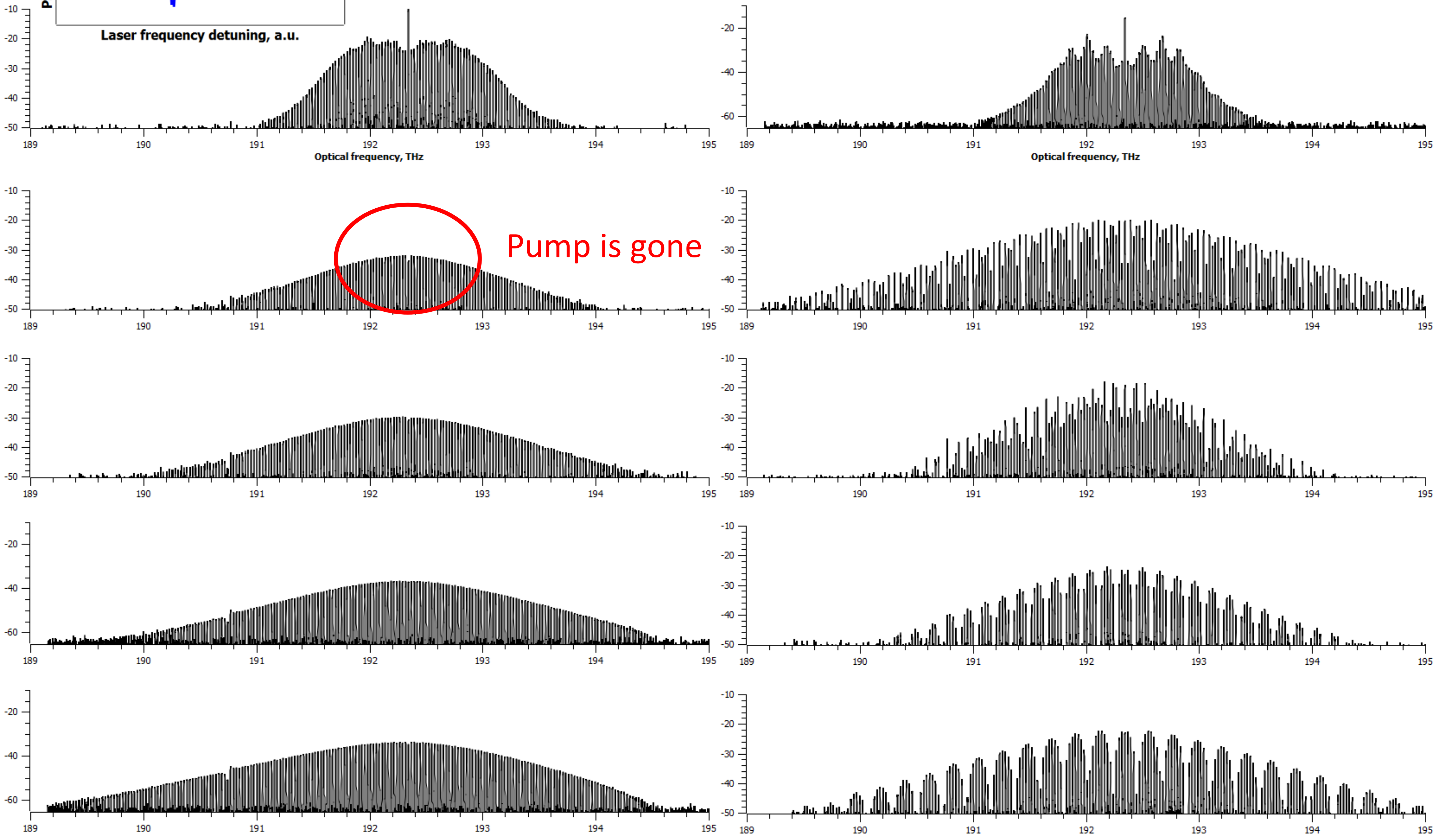
Image obtained by Risaku Toda, optical profilometer MDL JPL.

- Surface scattering limited (intrinsic) $Q=10^9$ @ 1561 nm.
- Single TE mode operation (TM is suppressed)
- Dispersion engineering

Solitons in MgF_2 PBR, 25.8 GHz



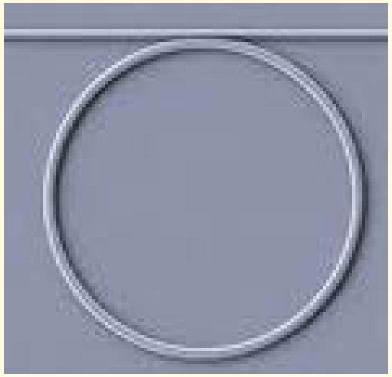
Characteristic soliton steps in transmission



PBR features and prospects

- Probably the most efficient dispersion engineered microcomb
- Fluoride crystals and other materials
- $Q>10^9$, compact optical mode volume = efficient comb generation
- UV, visible, near-IR and mid-IR operation
- Soliton states demonstrated
- Dispersion engineering for octave comb span
- Single mode operation

Next step: broadband solitons



- Heterogeneous integration, or
- fluoride chip based comb generators

PBR challenges

Fabrication

Significant dispersion change is achieved by 50 nm geometry modification

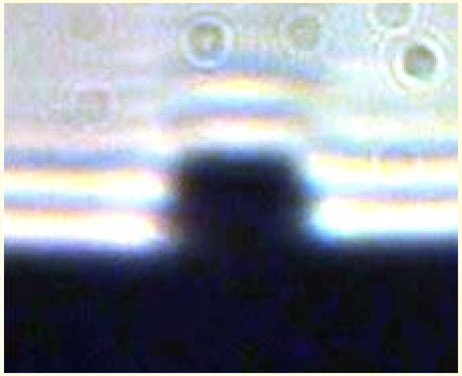
Current fabrication precision ~ 500 nm.

Imaging

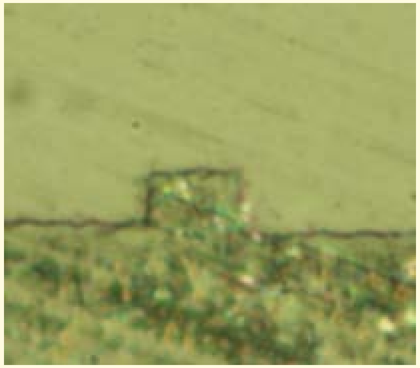
SEM – leads to surface charging effects, requires coating, slow

Profilometer – not capable of side wall imaging, slow

Imprint lithographic method – new technique, fast (2-3 hours)



Optical 500x



Micro-imprint