UNIVERSITY OF LATVIA

Kerr comb generation in silica WGM micro-resonators and application to telecommunications

Janis Alnis

International Symposium
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Funding:
ERDF No 1.1.1.1/18/A/155

Cooperation

Silica SiO_2 microsphere melting and WGMR testing for (bio)sensors, COMSOL modeling

University of Latvia, Institute of Atomic Physics and Spectroscopy,

Laboratory of Quantum Optics

J. Alnis, I. Brice, R. Veilande, K. Draguns, A. Sedulis

University of Latvia, Institute of Astronomy

R. Ganeev, A. Atvars

SiO_2 resonator for 1.55 mkm Telecom Microcomb

Riga Technical University , Institute of Telecommunications

T. Salgals, S. Spolitis, V. Bobrovs

Reproducible size silica microspheres by fusion splicer, theory, joint publications

Institute of Applied Physics of the Russian Academy of Sciences, Nizhny Novgorod

E. A. Anashkina, A. V. Andrianov

CO_2 machined Microrod resonators, chips

Max Planck Institute for the Science of Light, Erlangen,

Microphotonics research group

P. Del'Haye, Toby By

Quantum Optics Lab
Started in 2013, in the new Science building since 2019

Menlo Systems fiber based Optical frequency comb

760 VCSEL, 780 nm ECDL, 1550 nm laser, Rb saturation, spectrometers, microscopes

SiO_2 microsphere melting on oxy-hydrogen flame , CO_2 laser,

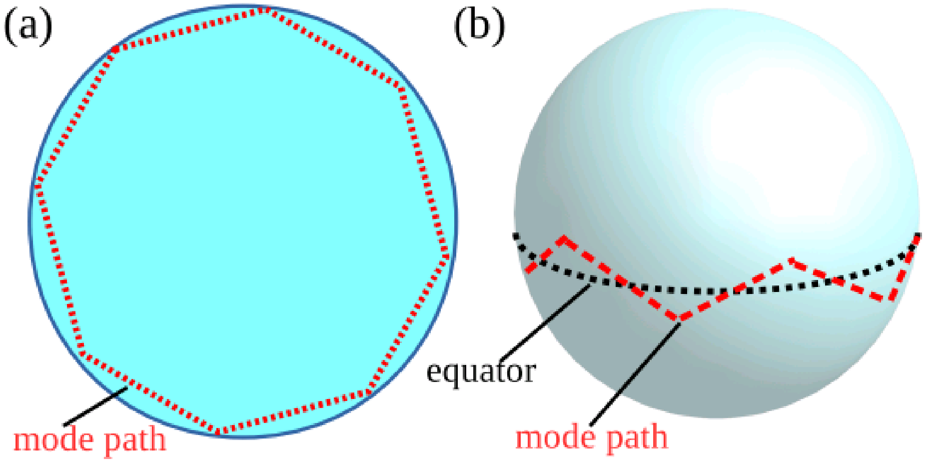
Whispering gallery mode resonator setups: prism, tapered fiber, in liquid for biosensors, comb

Whispering gallery mode microresonators

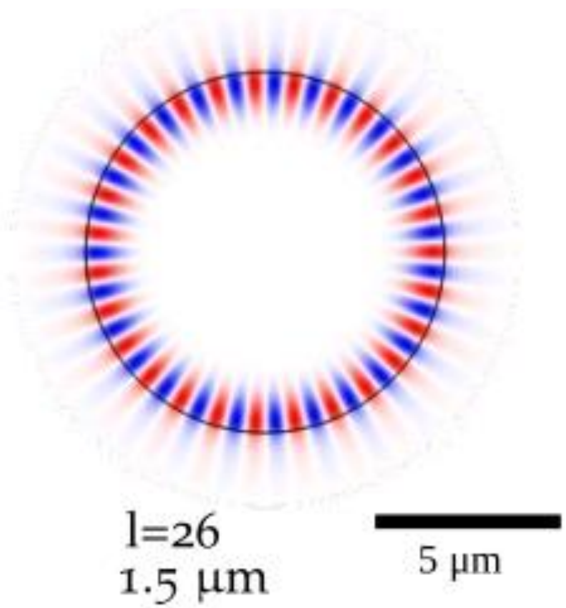
- Based on total internal reflection
- Do not need mirror coatings
- Work in broad wavelength range
- WGMR sensors, nonlinear optics

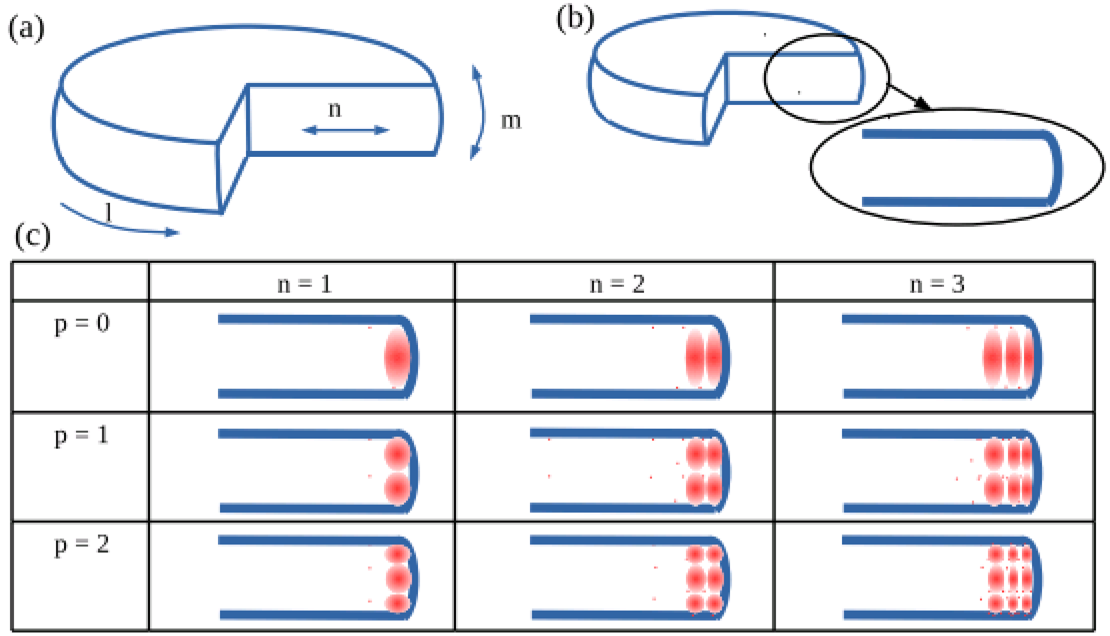
Accoustics

Classical optics

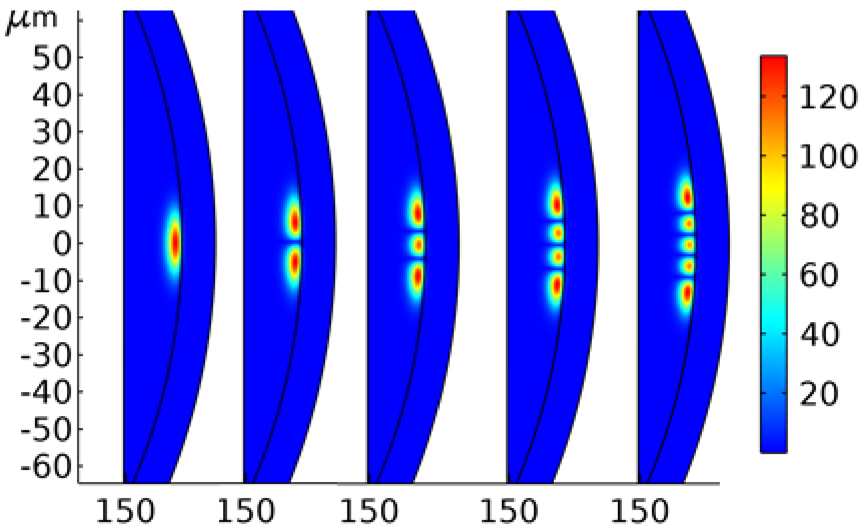


Wave optics, COMSOL modeling

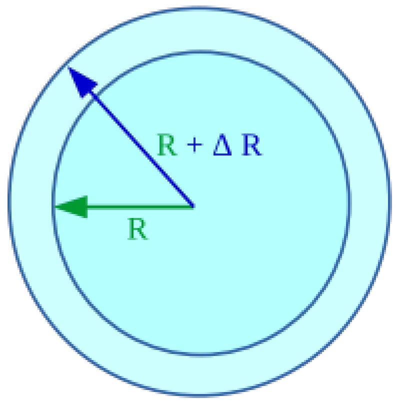


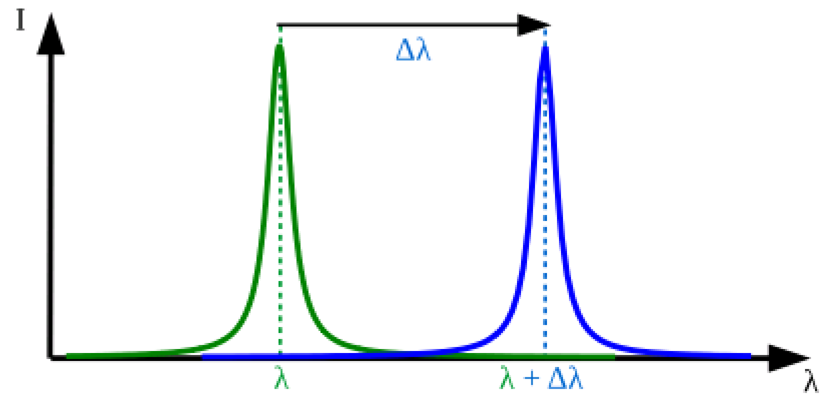


Understanding different WGMs: (a) radial mode number n, azimuthal mode number l and polar mode number m dirctions; (b) the region for plane sliced from a microsphere WGM resonator and (c) the intensity distributions for various modes in the slice.



Whispering gallery mode resonators





Optical quality factor Q

Q = $\boldsymbol{\upsilon / \Delta \upsilon}$ where υ is optical frequency $\Delta \upsilon$ linewidth

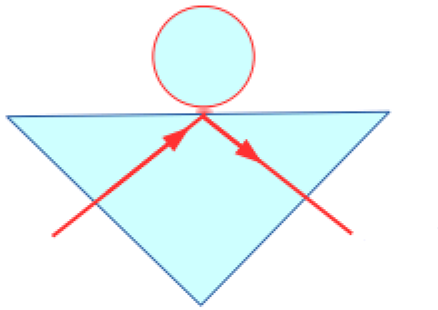
Q = $\boldsymbol{\omega \tau}$ where $\boldsymbol{\tau}$ is the phton lifetime

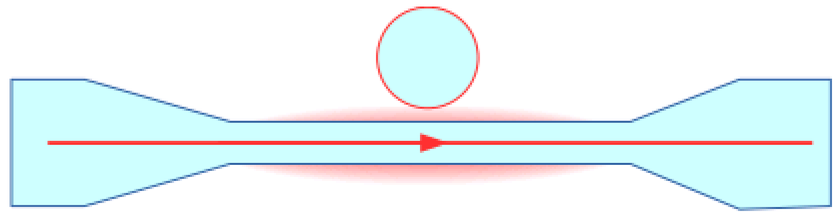
Q = 2π L / λ where L is the photon path length.

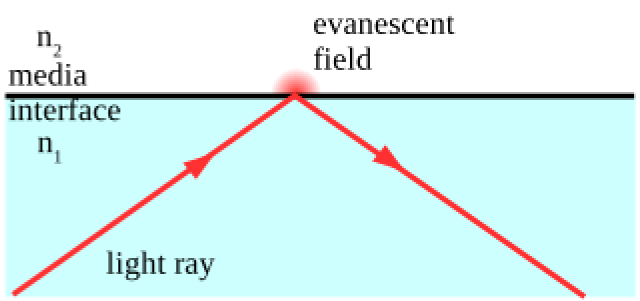
<u>Examples.</u>
Resonator Q factor 10^8 . Light runs 25 m in 1 mm sphere.

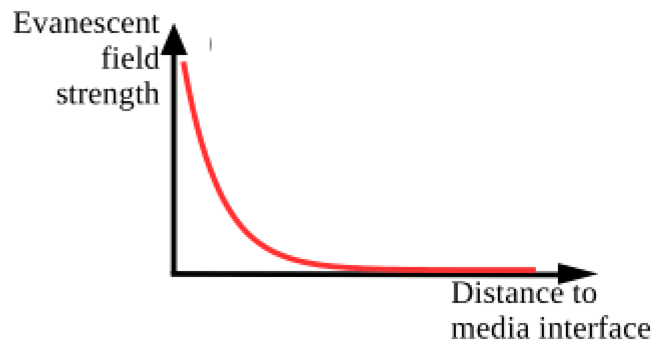
We demonstrated:
Whispering gallery mode resonator and glucose oxidase based glucose biosensor
I. Brice et al Sensors and Actuators B, 2020

Prism and tapered fiber coupling
free space focussing – not efficient , mostly reflected

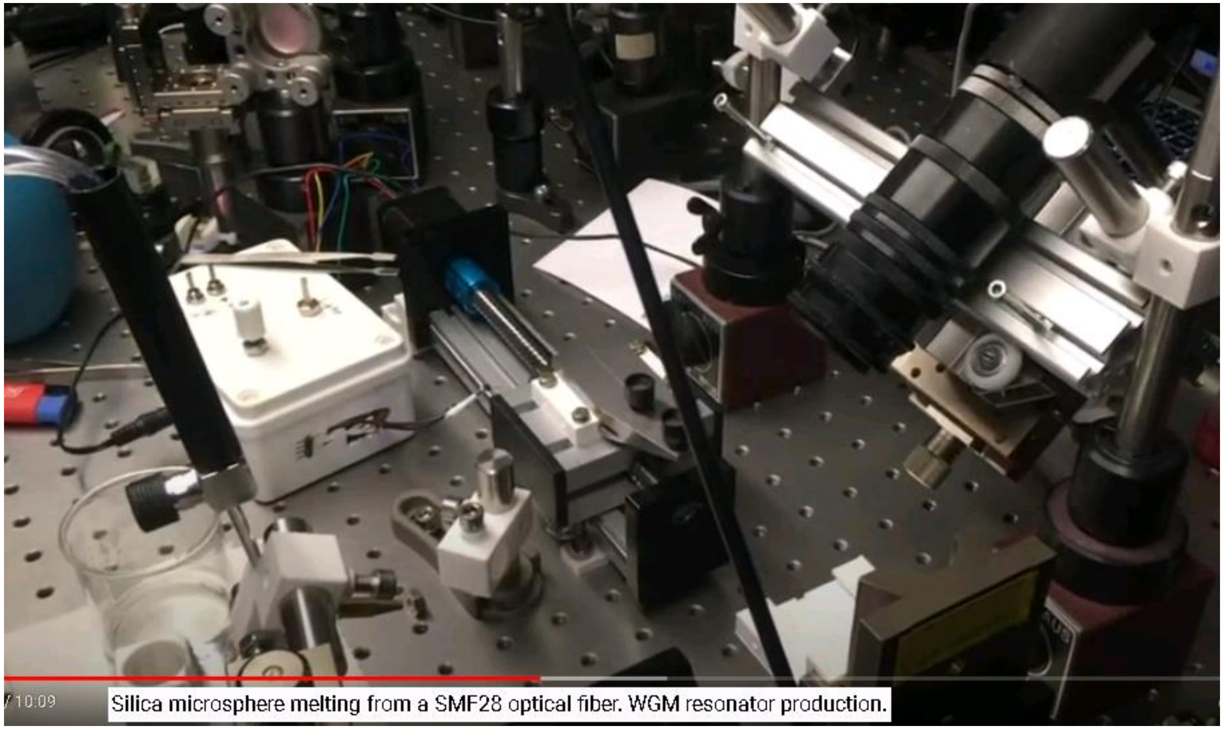


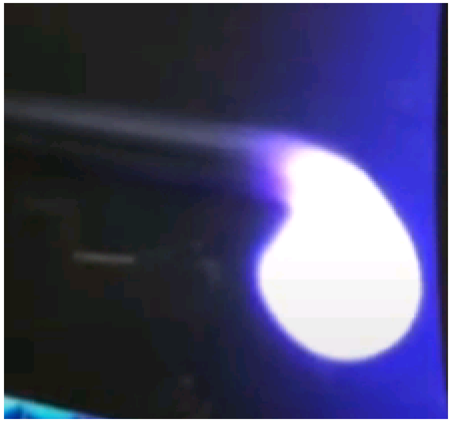


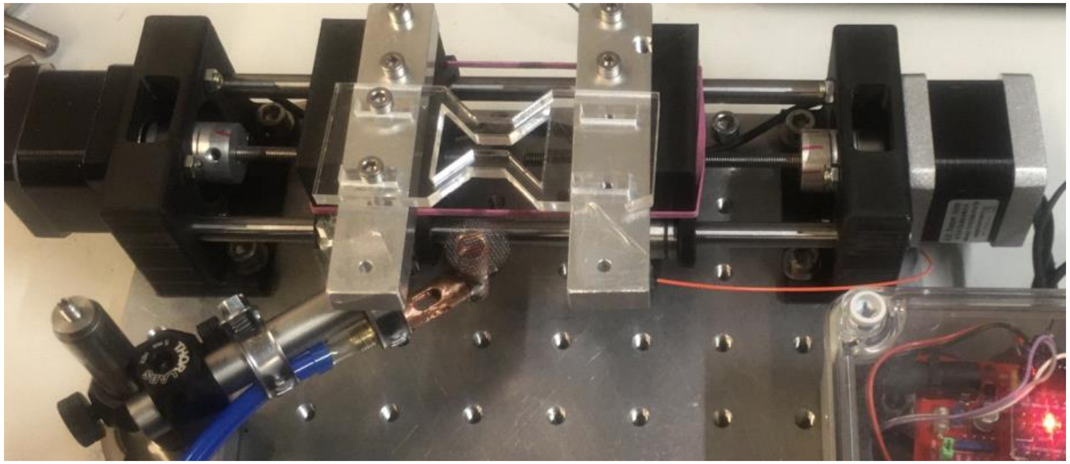




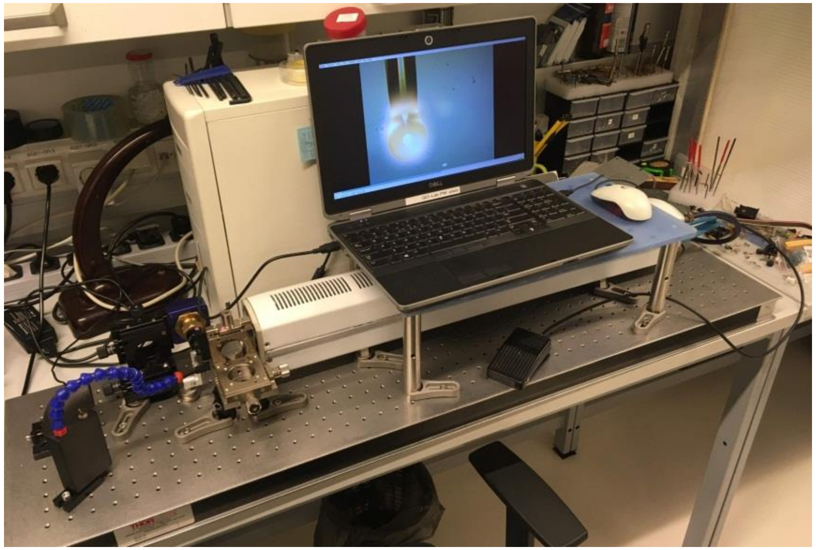
Microsphere fabrication in ohy-hydrogen flame
tapered fiber pulling in pure hydrogen or propane flame

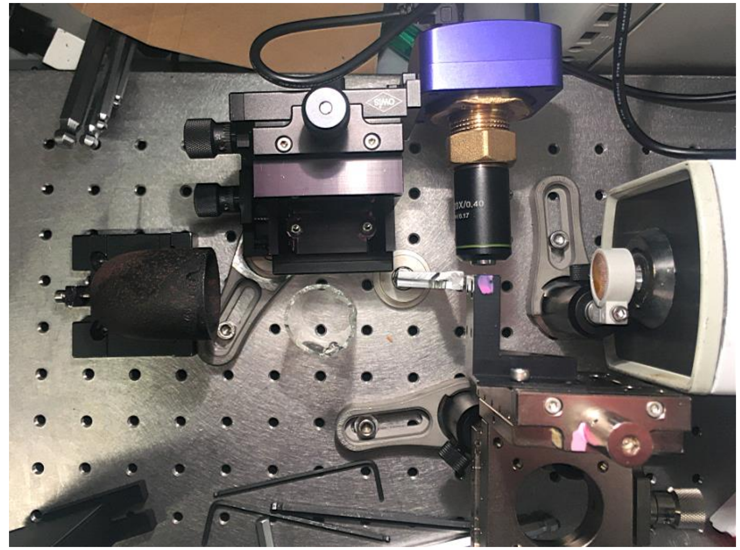






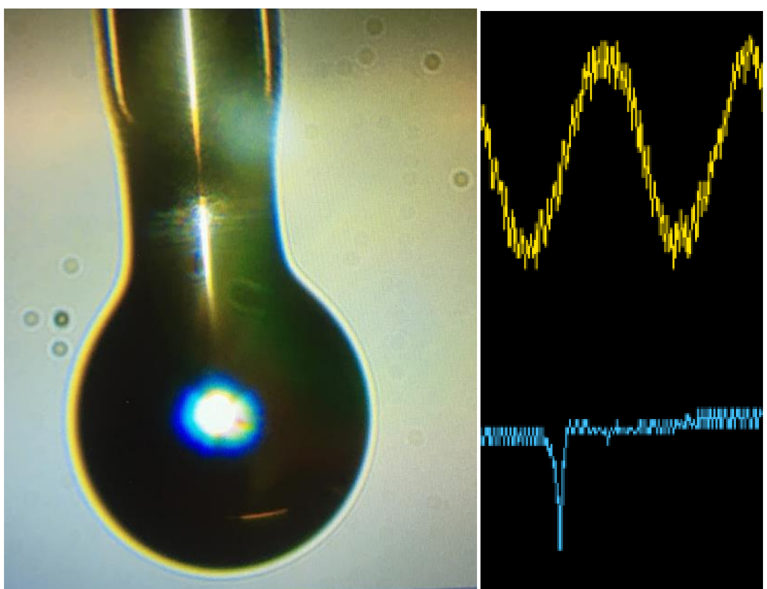
Microspheres and microrods fabricated with a 40W CO_2 laser lathe





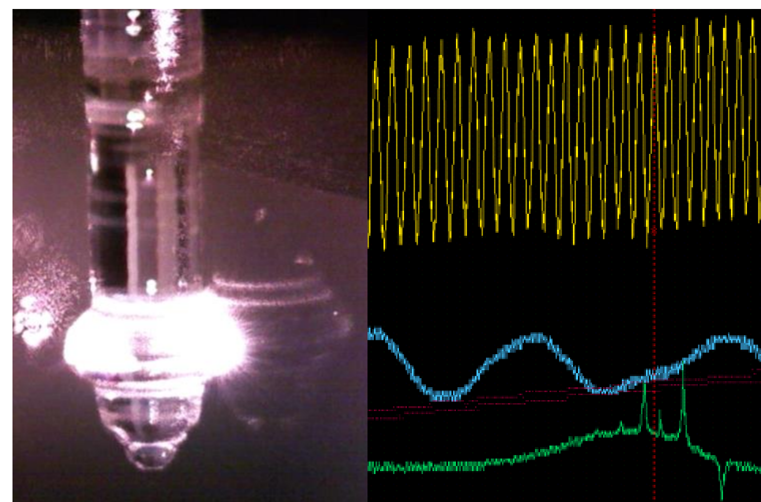
Home-made microscope: 20x objective from Ebay (60 EUR) and Astronomy webcam (150 EUR)

Sphere WGMR FWHM = 2 MHz **Q = 2E8 at 780 nm**



Yellow reference interference fringes from fiber etalon have 50 MHz period.

Microrod CO_2 lathe
first resonances Q ~ 10^6.
Evaporated silica dust is a problem



Microsphere resonator combs

For Kerr effect (modifying the index of refraction) intensities ~ 1 GW/cm^2 are necessary
Kerr effect has been usually observed with pulsed lasers
In microspheres it is possible with a CW laser

Peak intensity and circulating power calculations

power circulating $P_{circ} = P_{in} Q \frac{\lambda}{\pi^2 n R} \frac{K}{(1+K)^2}$

λ is the resonance wavelength, R is the devic
Q is the quality factor of the device,
n is the effective refractive index
K is the coupling coefficient

transmission: $T = \frac{(1-K)^2}{(1+K)^2}$

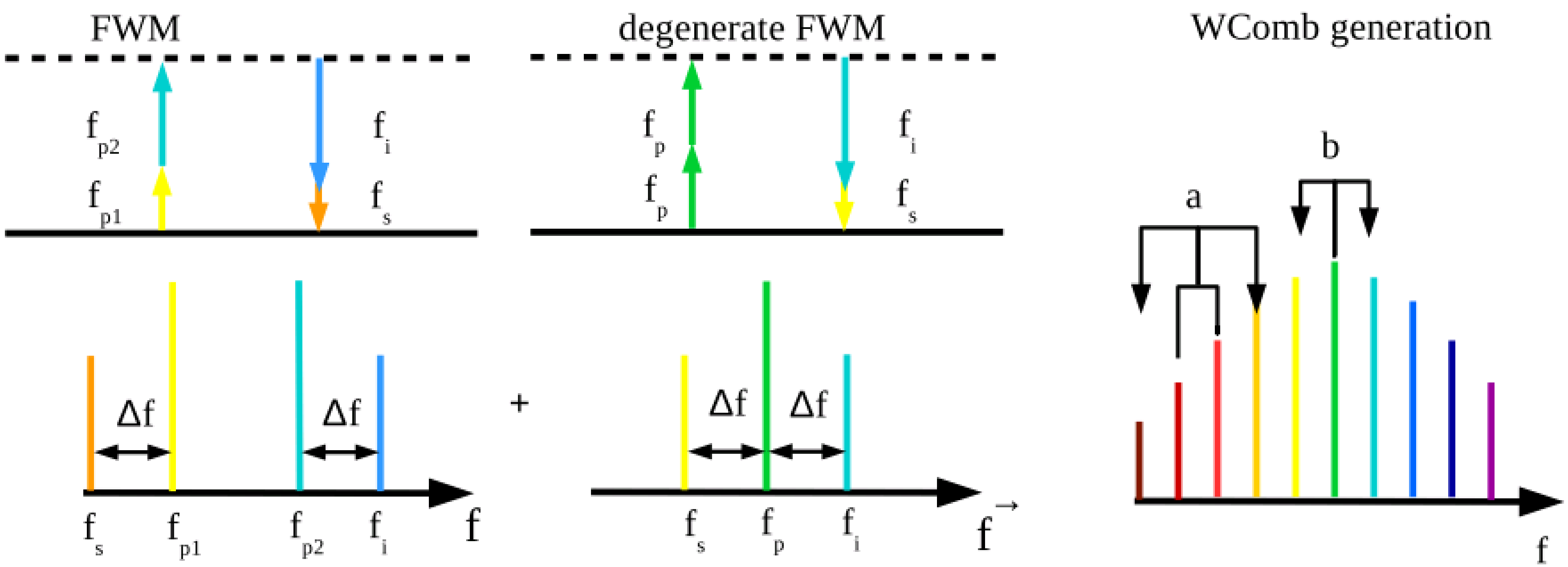
intensity circulating P_{circ}/A_m,

mode area $A_m = \frac{\int \varepsilon(r)|E|^2 dA}{\max(\varepsilon(r)|E|^2)}$

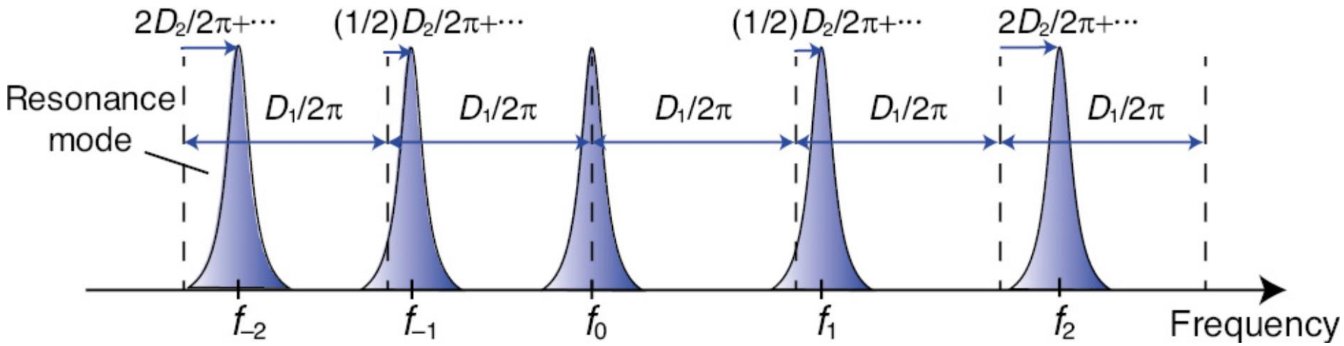
Power and optical intensity circling inside the WGMR from 0.1 W input laser power.

R, µm	Q ·10^7	T	K	Q_{intr} ·10^7	P_{circ} W	A_{eff}, µm^2	I_{circ}, GW/cm^2
135	2.0	0.17	1.69	5.4	1016	36.15	2.8
60	1.2	0.26	2.05	3.7	1468	18.45	8.0
85	4.6	0.54	3.89	22.0	4671	24.62	19.0
83	5.2	0.14	1.61	13.6	4217	24.14	17.5

Four Wave mixing (FWM) nonlinear process

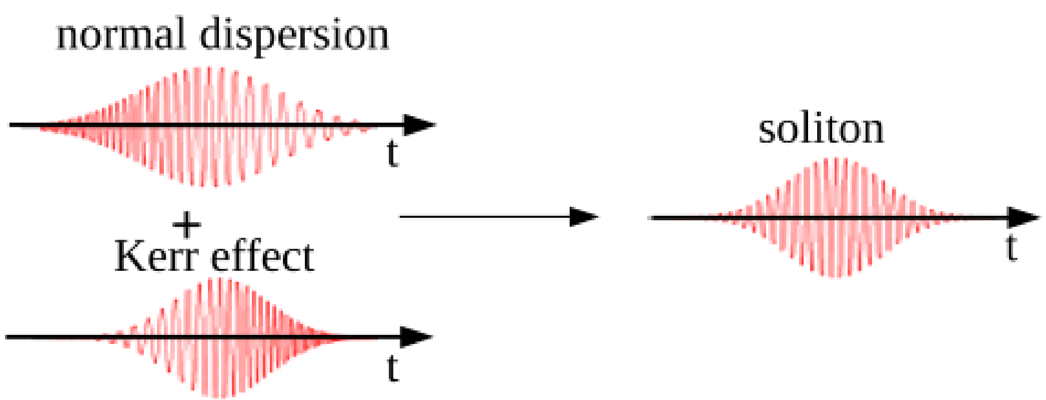


Dispersion caused detuning between comb and WGM lines



[S. Fujii, T. Tanabe, (2020) Dispersion engineering and measurement of whispering gallery mode microresonator for Kerr frequency comb generation, Nanophotonics 9, 1087–1104]

Dispersion compensation to make a broader comb microsphere size

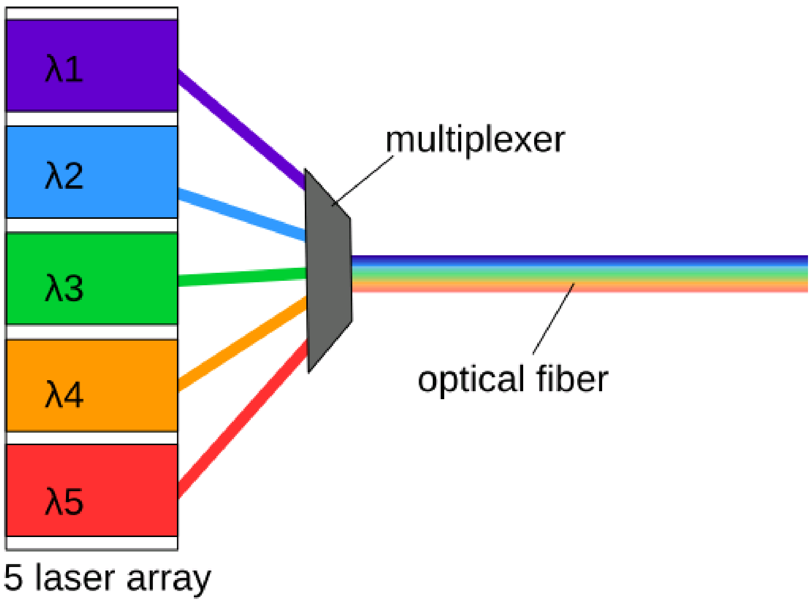


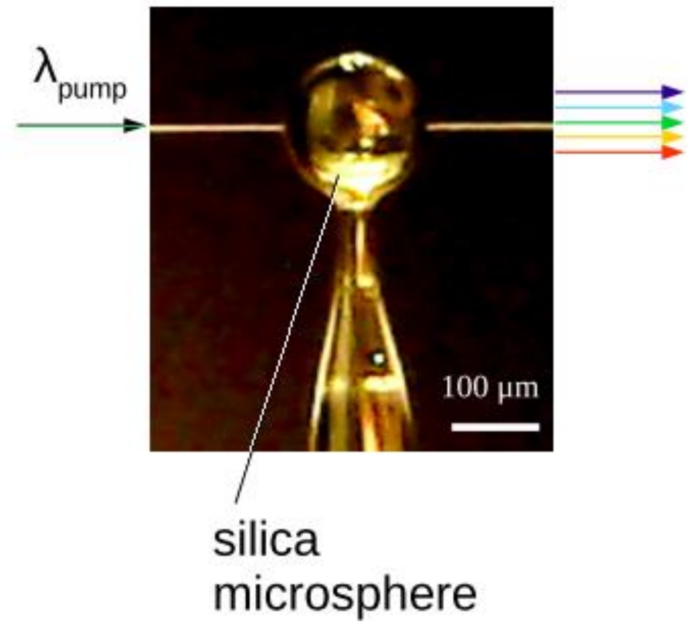
In soliton regime Kerr effect compensates dispersion.
In such case dispersion is 0 and pulse circulates without changing length.
Soliton regime is the mos stable regime, **hard to get.**

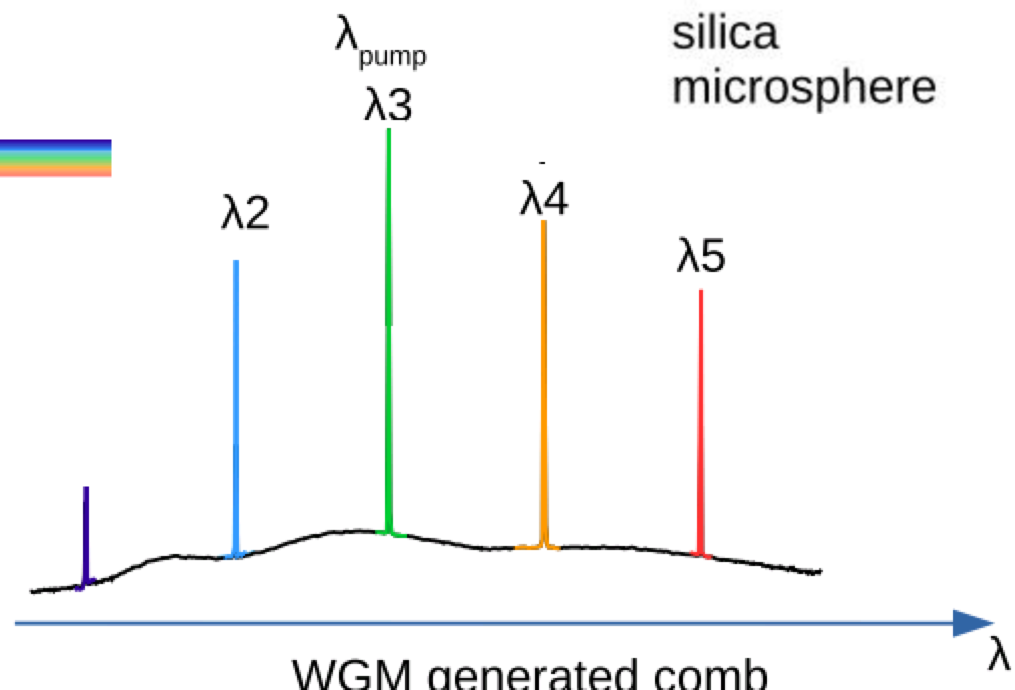
Vision for use in telecom

Wavelength Division Multiplexing

Replace laser array with frequency comb generated inside WGM resonator.

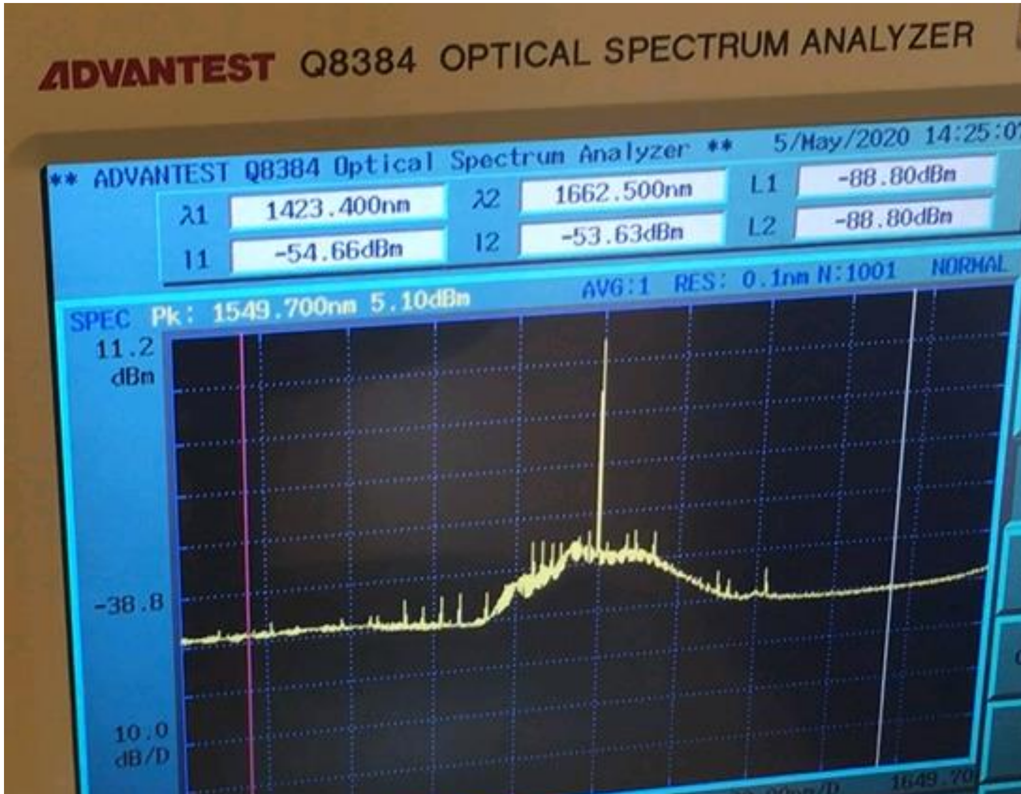


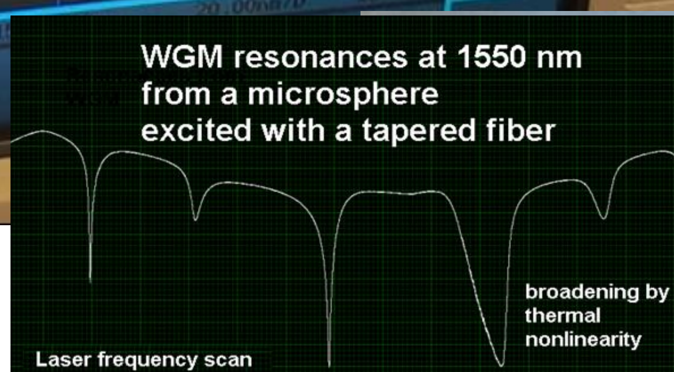




May 2020. Our first comb from SiO_2 microsphere.

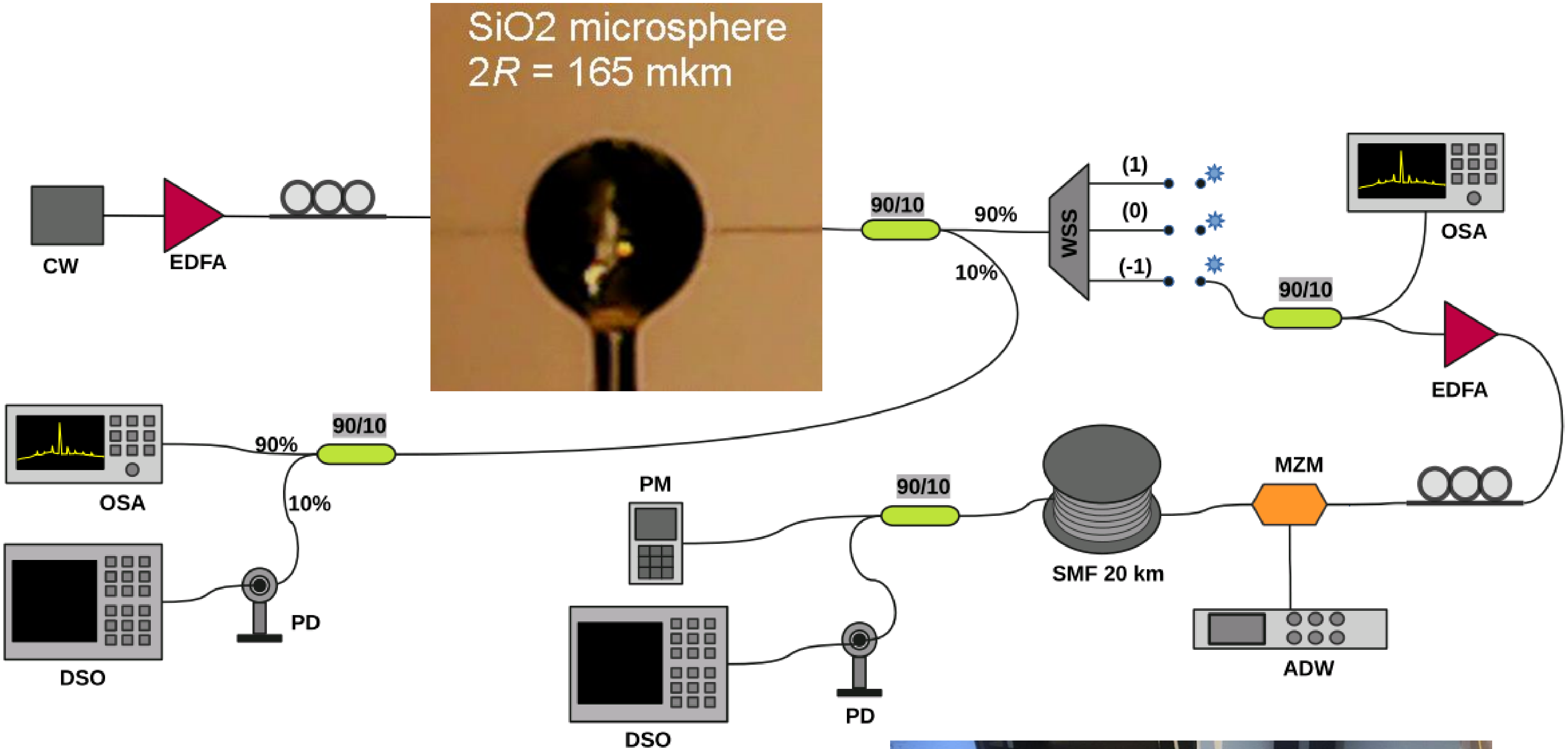
Weak and unstable in time. `

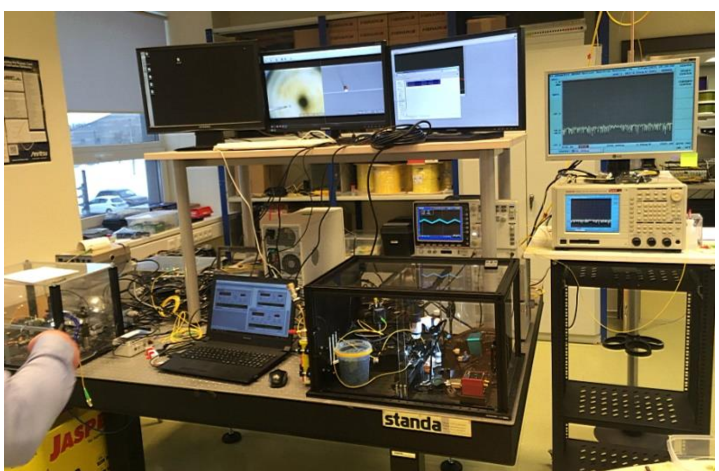


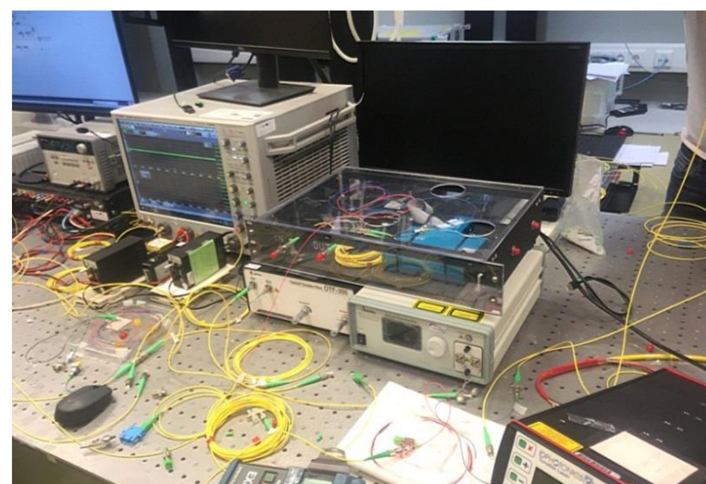


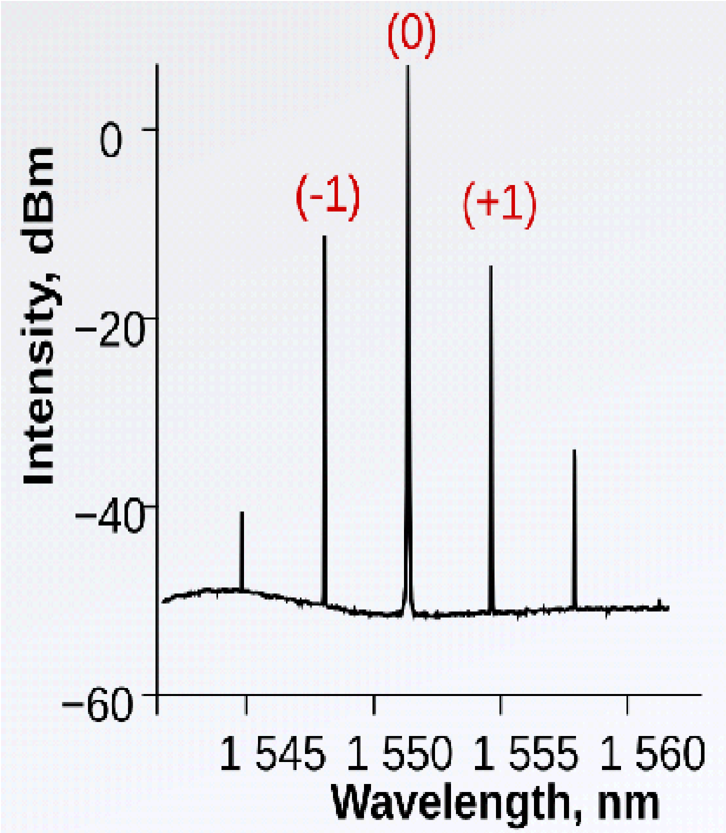
$Q \approx 3 \times 10^7$

Microsphere comb experiment for telecom

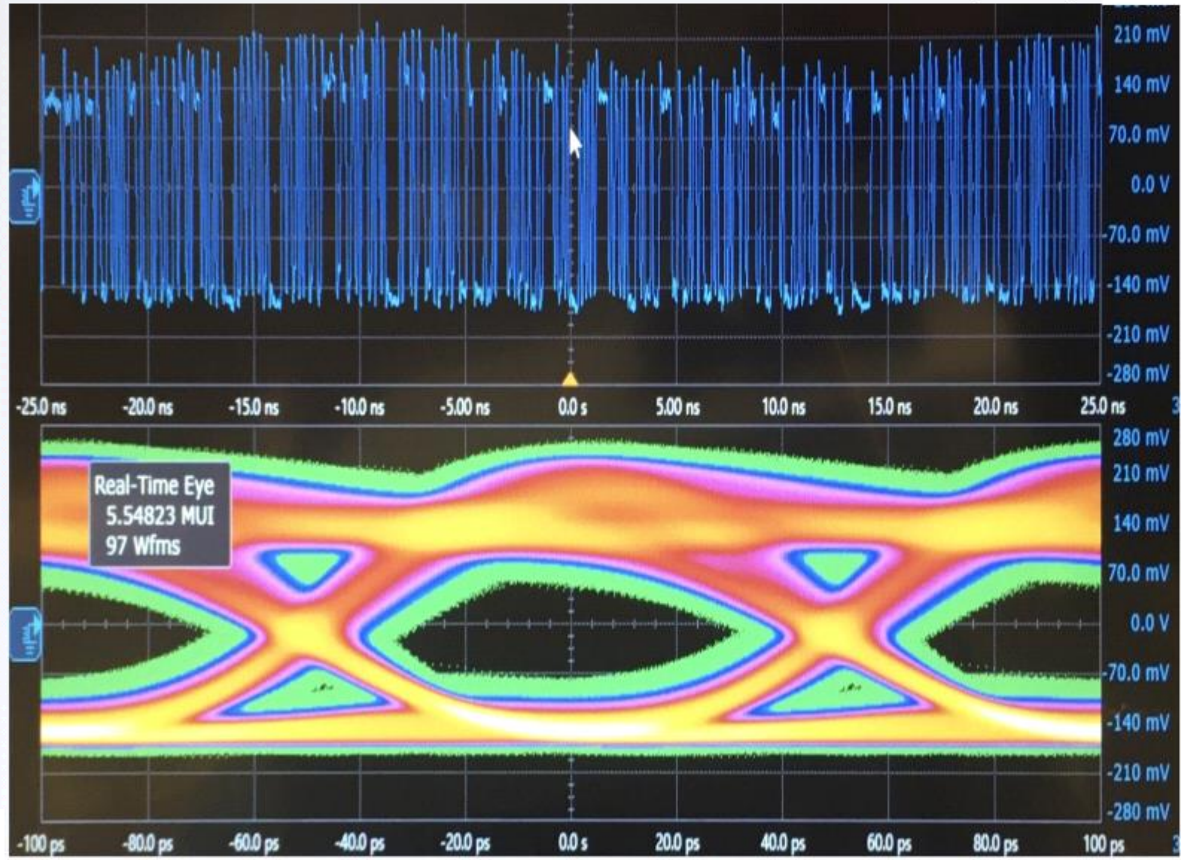








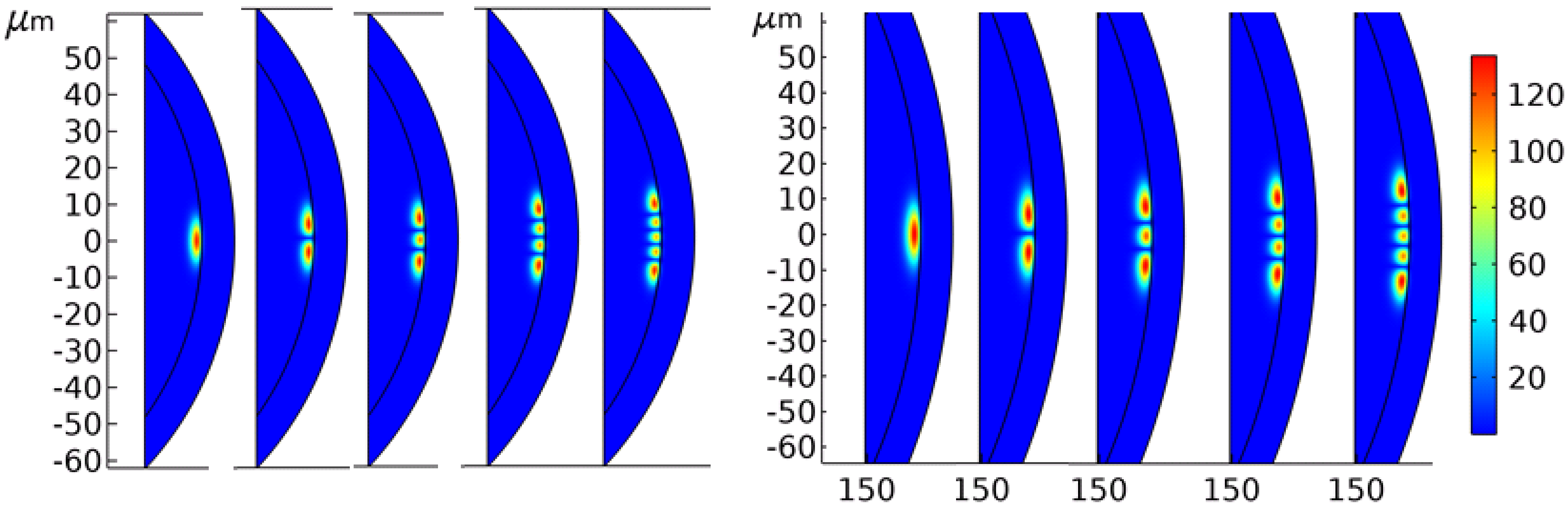
10 Gbit/s data and eye diagram on WDM selected OFC line (+1)

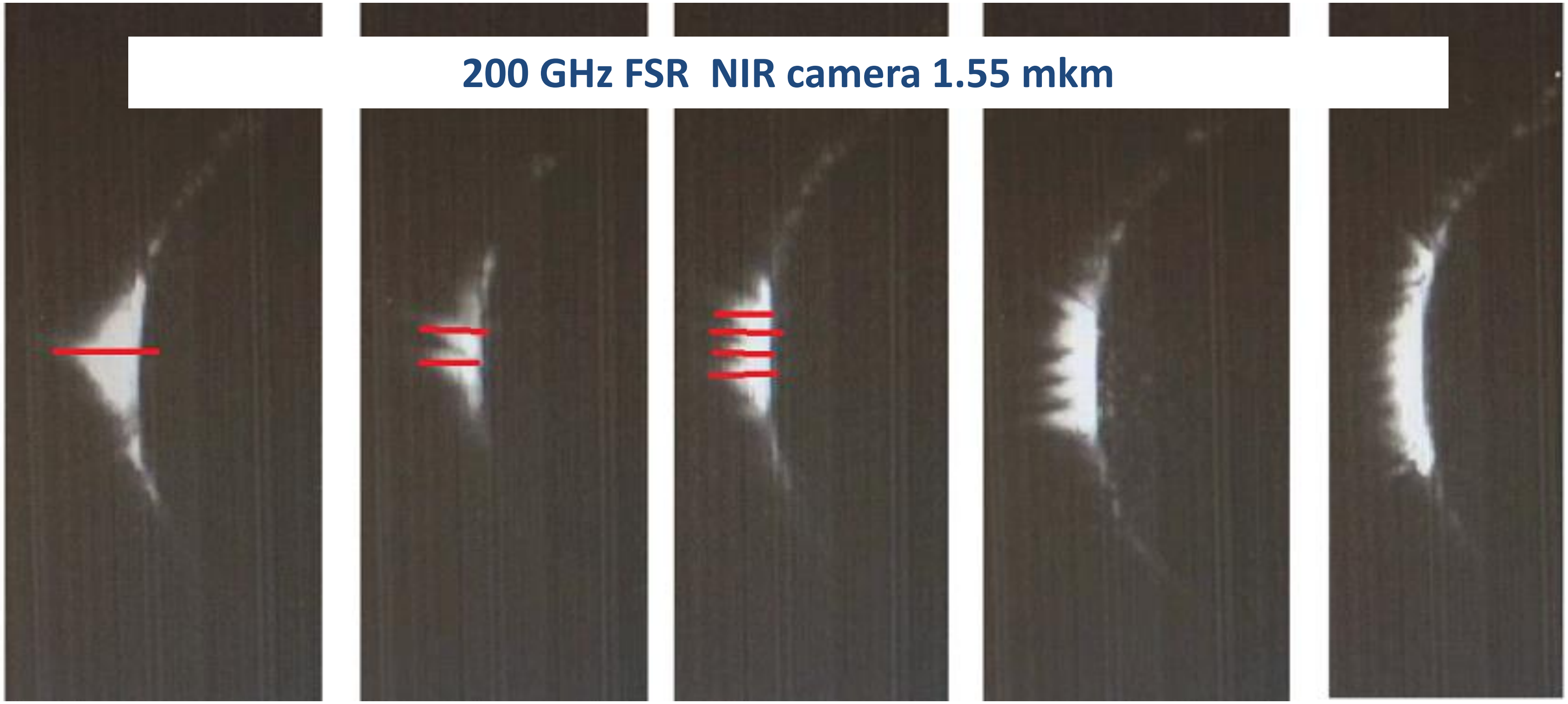


E.A. Anashkina, V. Bobrovs, T. Salgals, I. Brice, J. Alnis, A.V. Andrianov,
Kerr optical frequency combs with multi-FSR mode spacing in silica microspheres
IEEE Photonics Technology Letters 33, 453-456 (2021).

T. Salgals, J. Alnis, R. Murnieks, I. Brice, J. Porins, A. V. Andrianov, E. A. Anashkina, S. Spolitis, V. Bobrovs,
Demonstration of a fiber optical communication system employing a silica microsphere-based OFC source,Optics Express 29, 10903-10913 (2021).

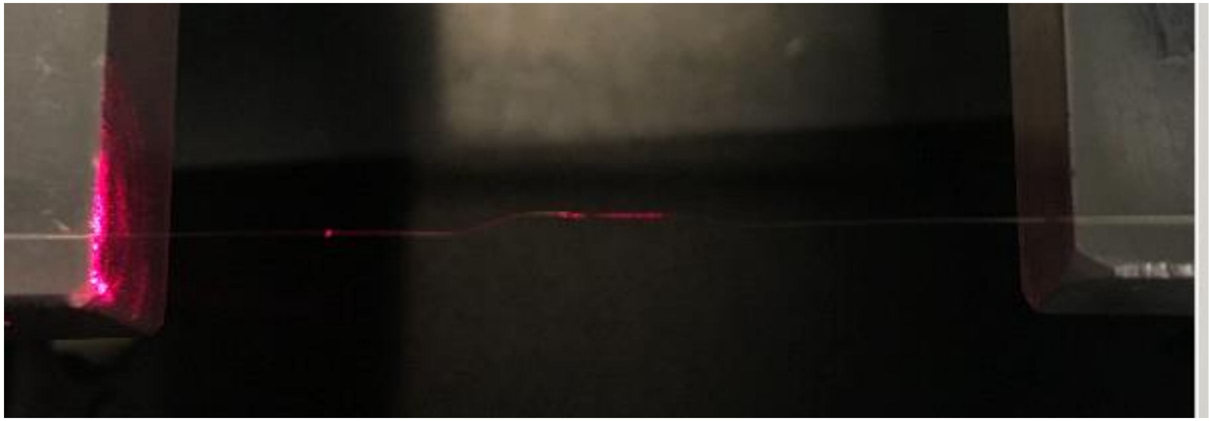
Microspheres FSR = 400 GHz and FSR = 200 GHz



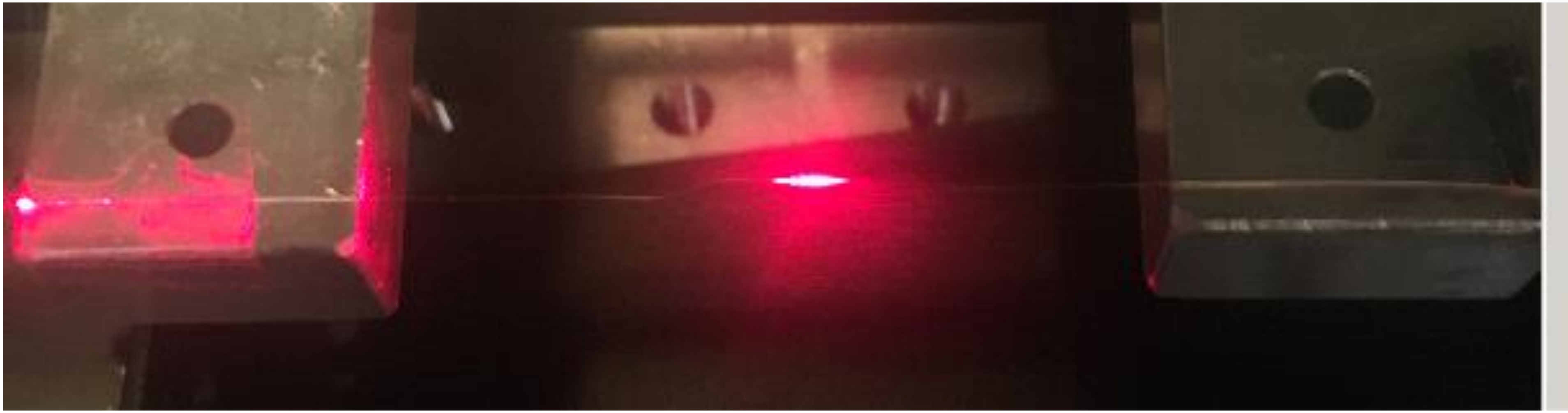


Silica surface degradation by humidity

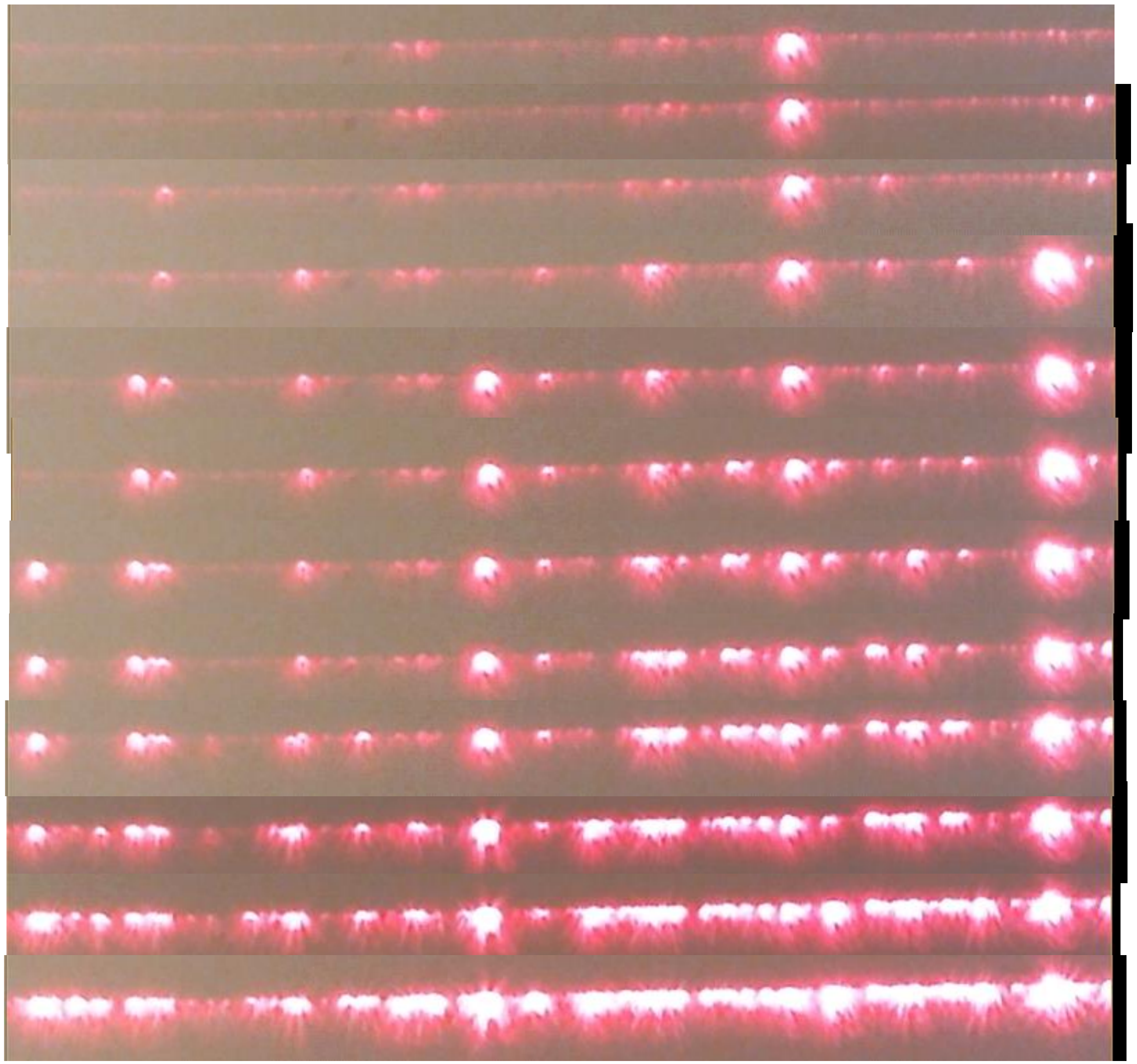
Tapered fiber freshly made



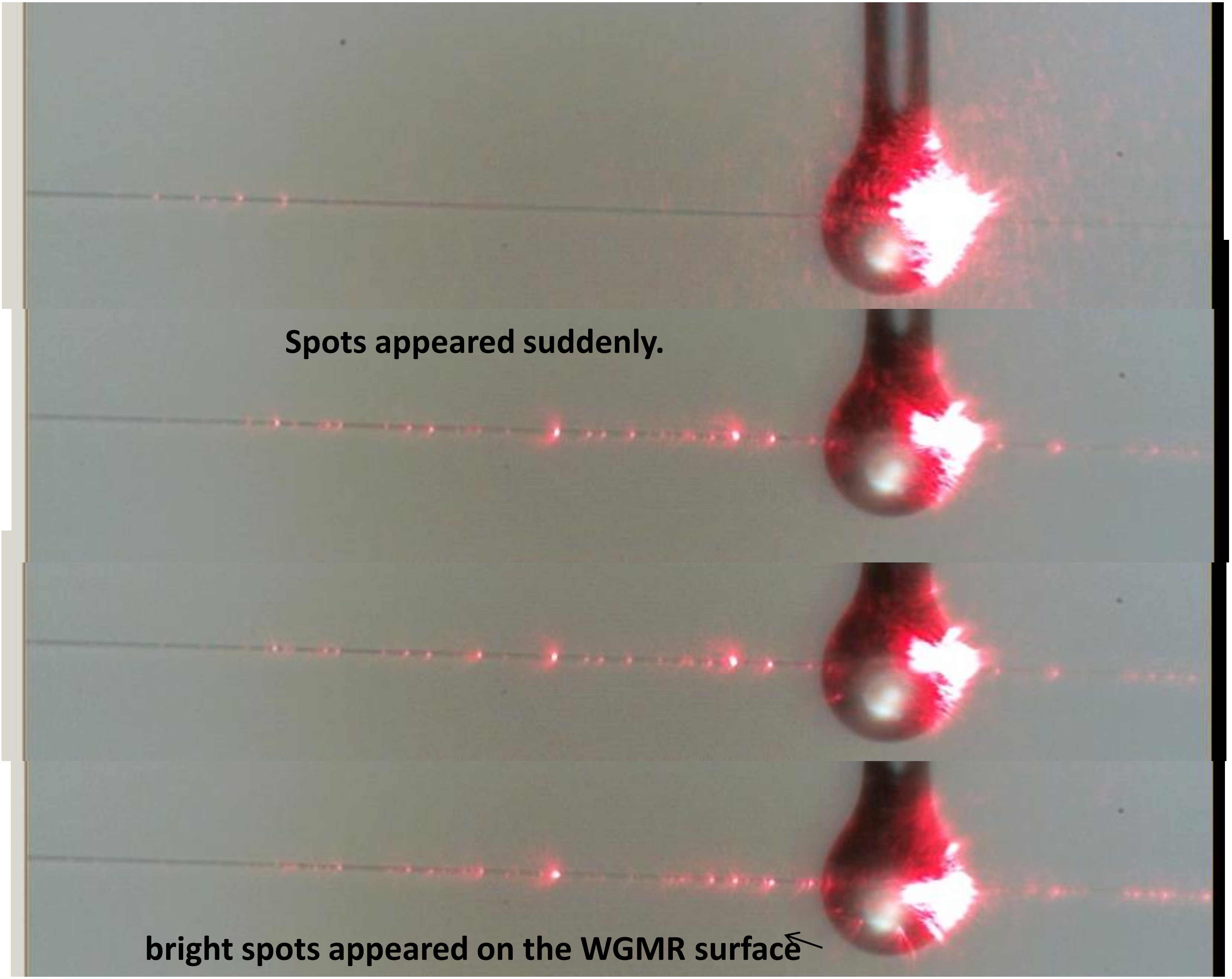
and one hour later at 70 % RH humidity



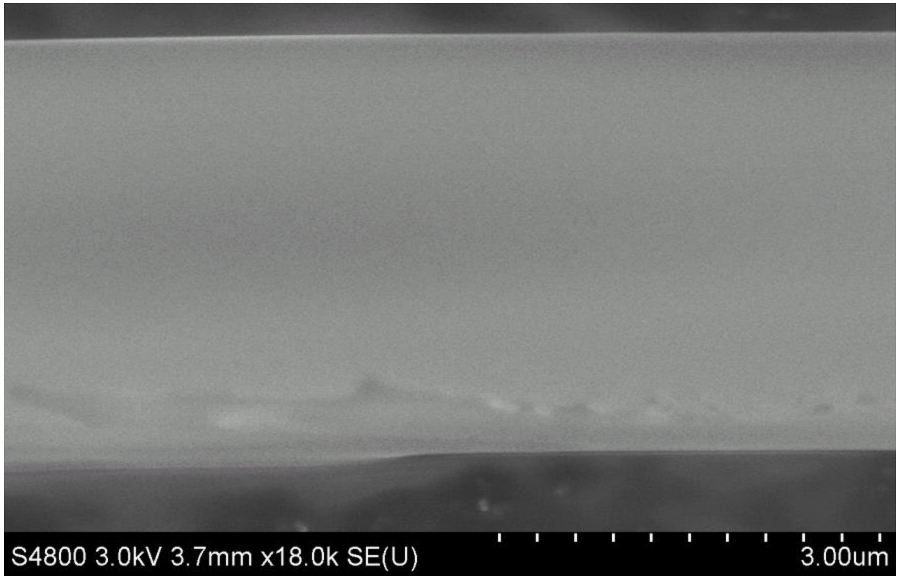
Tapered fiber degraded in 65 % RH within 2 hours
Cracks or quartz nanocrystals ?
Sylanol sites (-OH) (Raman specdtroscopy)

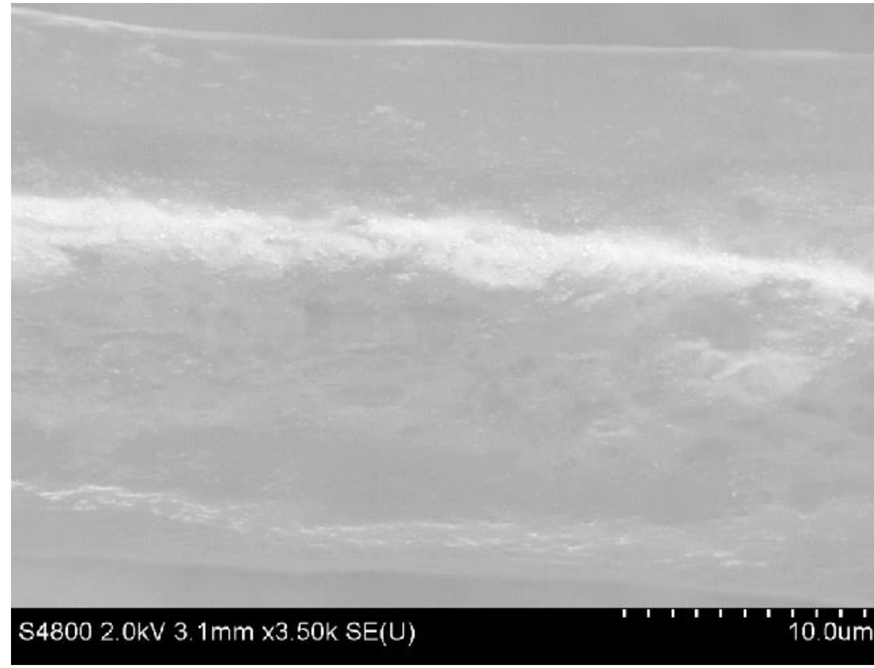


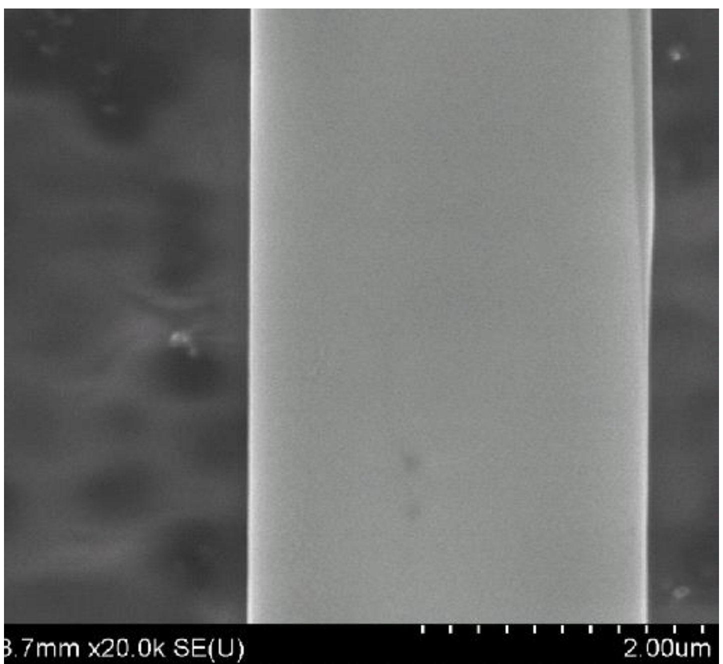
Microsphere degradation – bright spots appeared on the WGMR surface

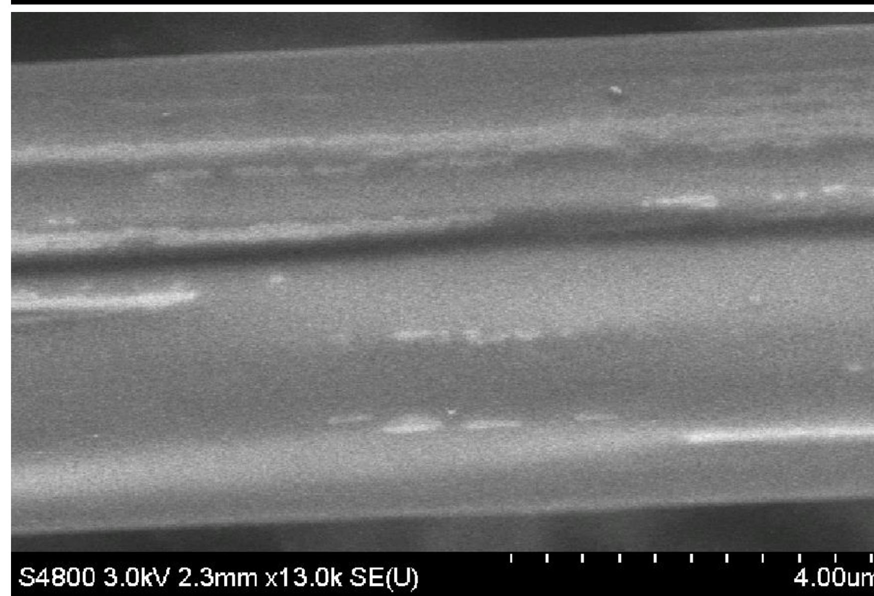


Tapered fiber after exposure to moisture fog
estimated fiber edge straightness variations ca 100 nm

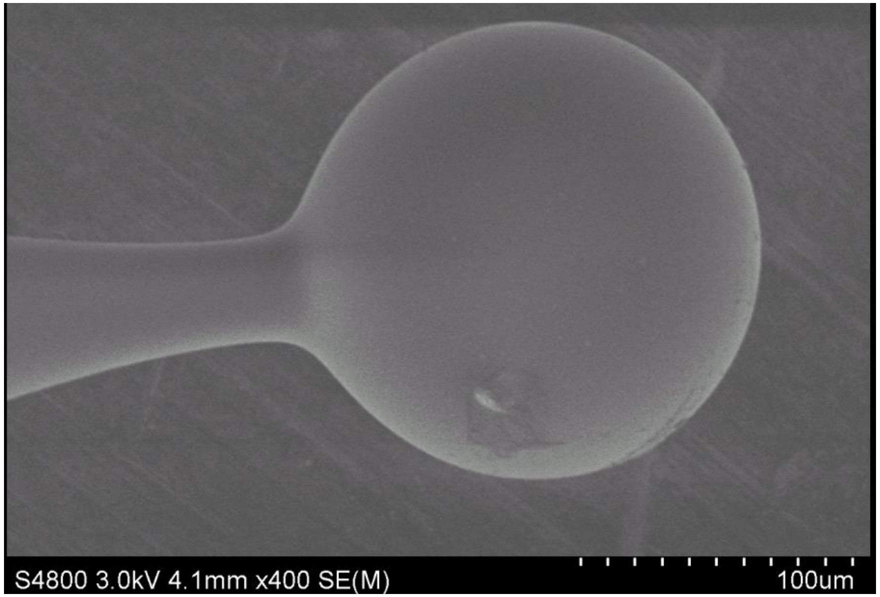


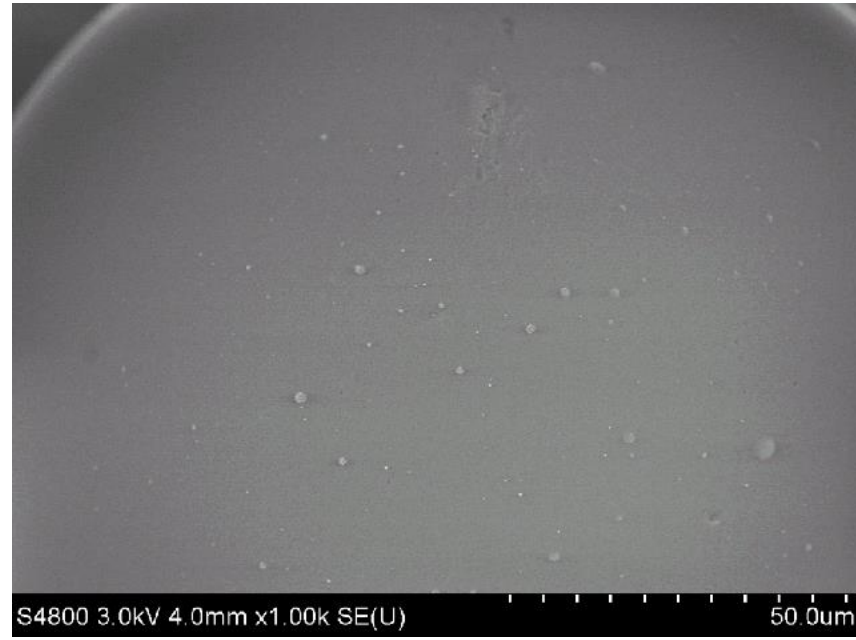


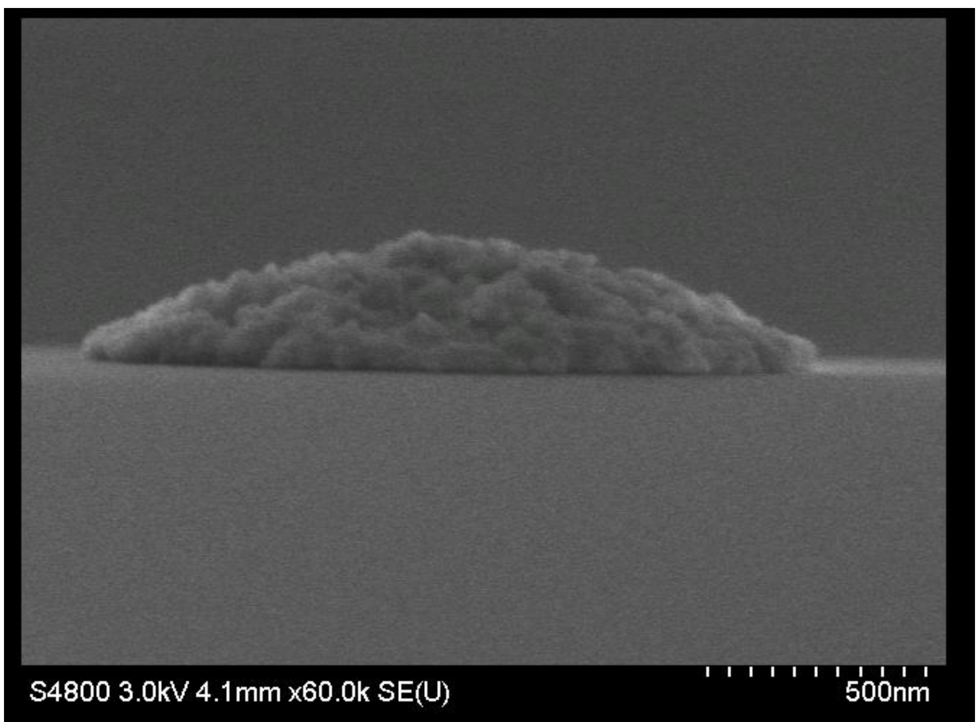


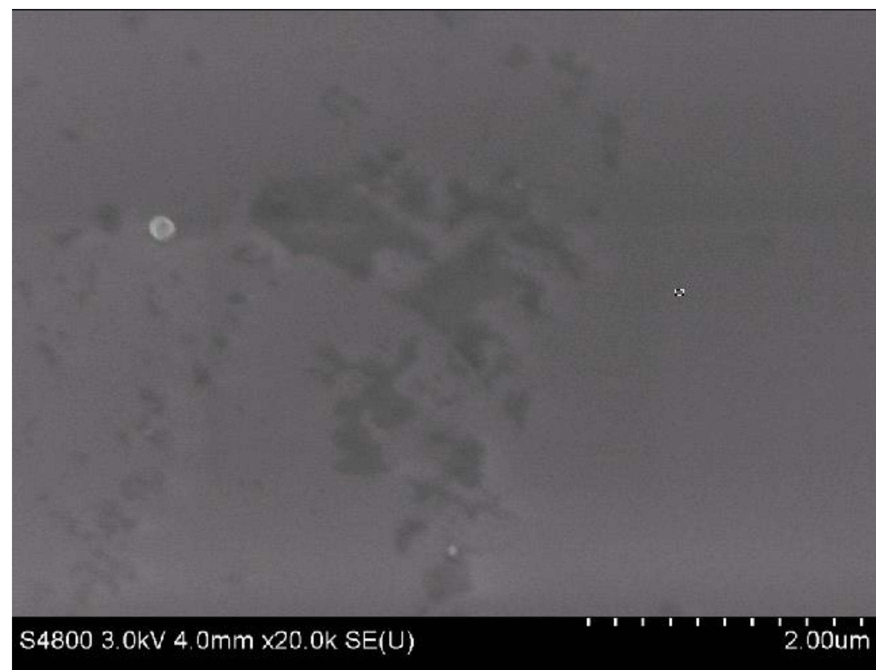


Resonator 1. It has been in humidity fog for 5 sec.



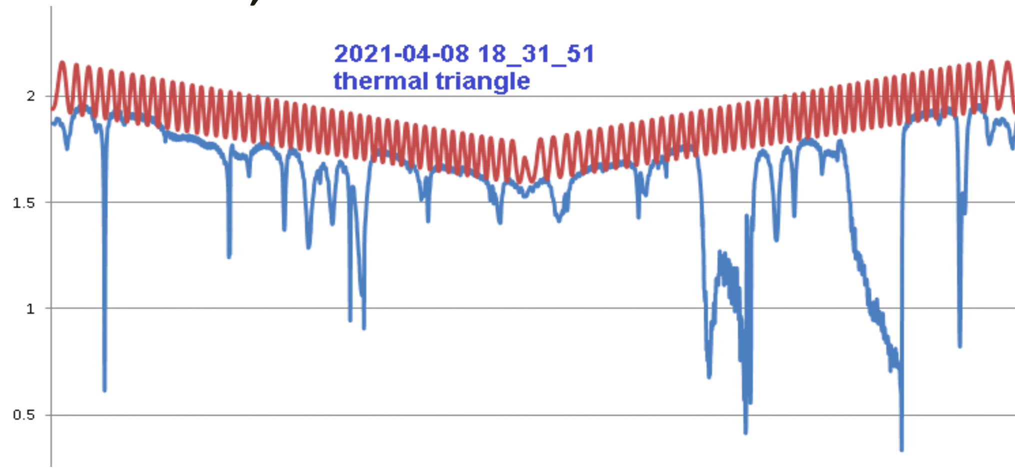


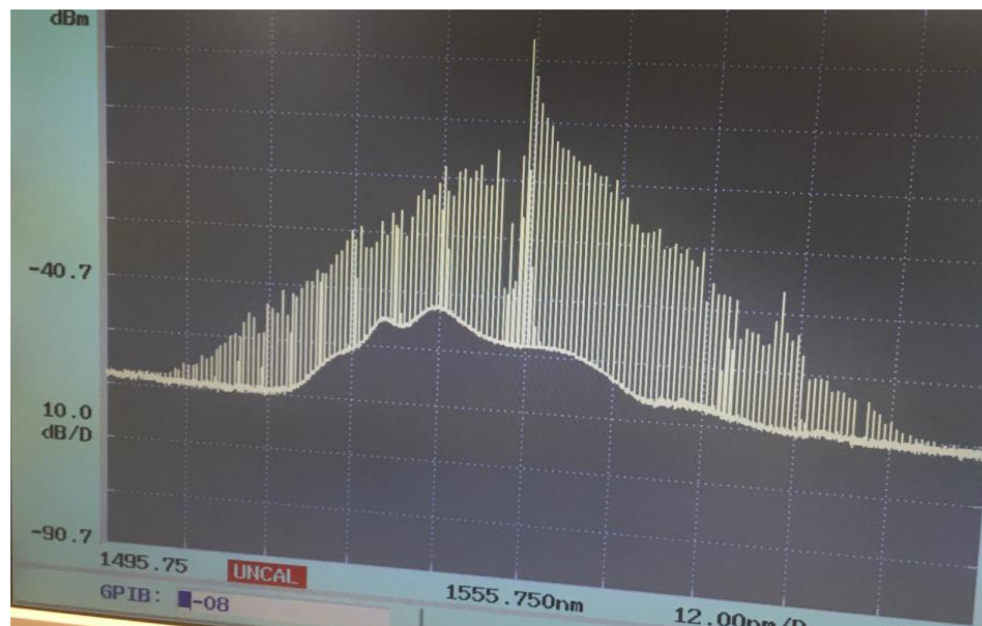




90 GHz FSR Microrod resonators from P. Del'Haye
Thermal triangles – thermal nonlinearity – necessary to see if we want to get combs.

With Thorlabs SFL1550 tunable laser, not attenuated, no EDFA.

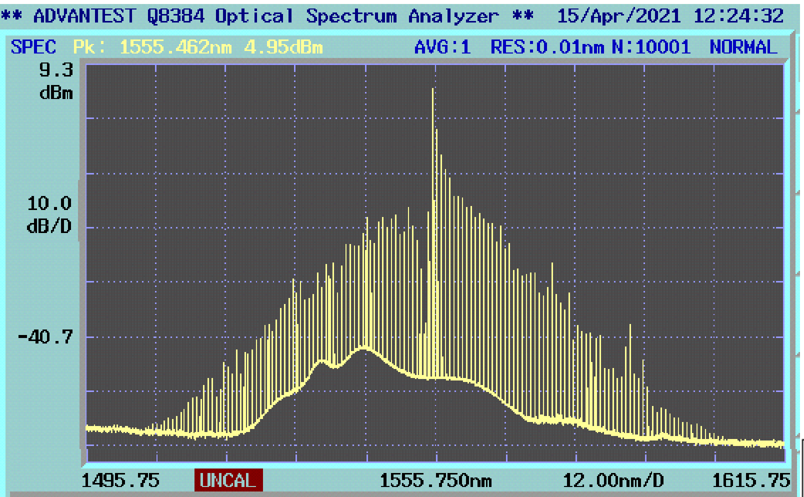


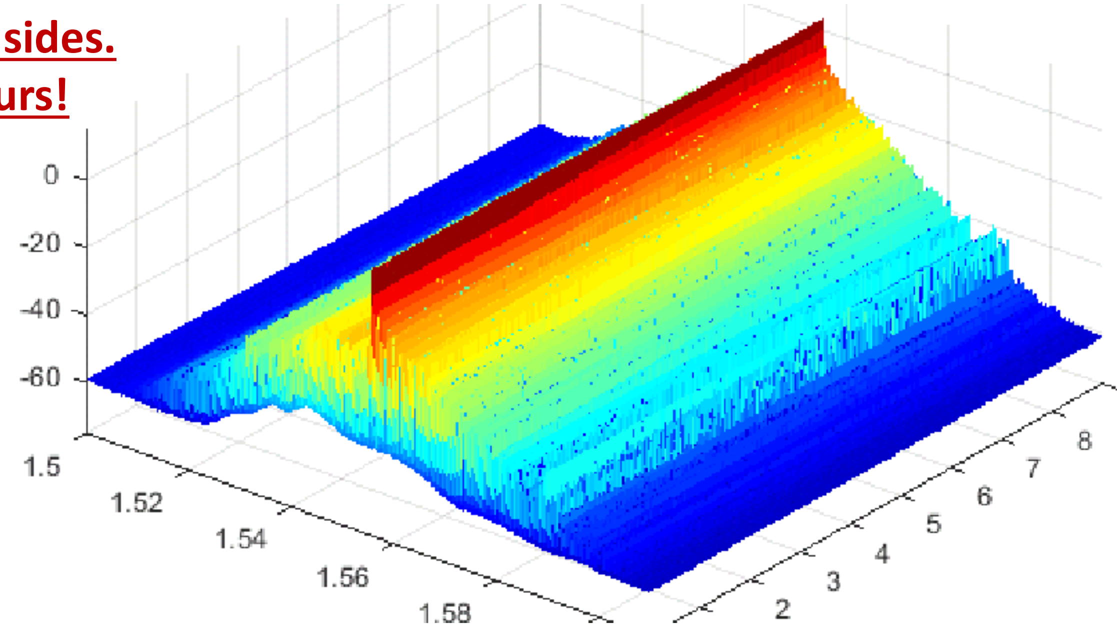


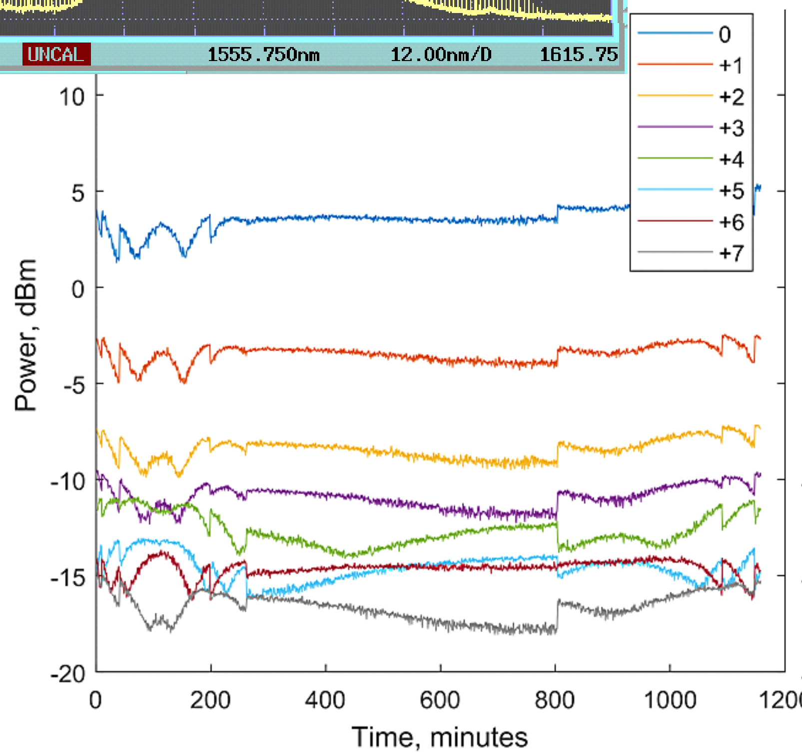
Pumping with single laser from two sides.

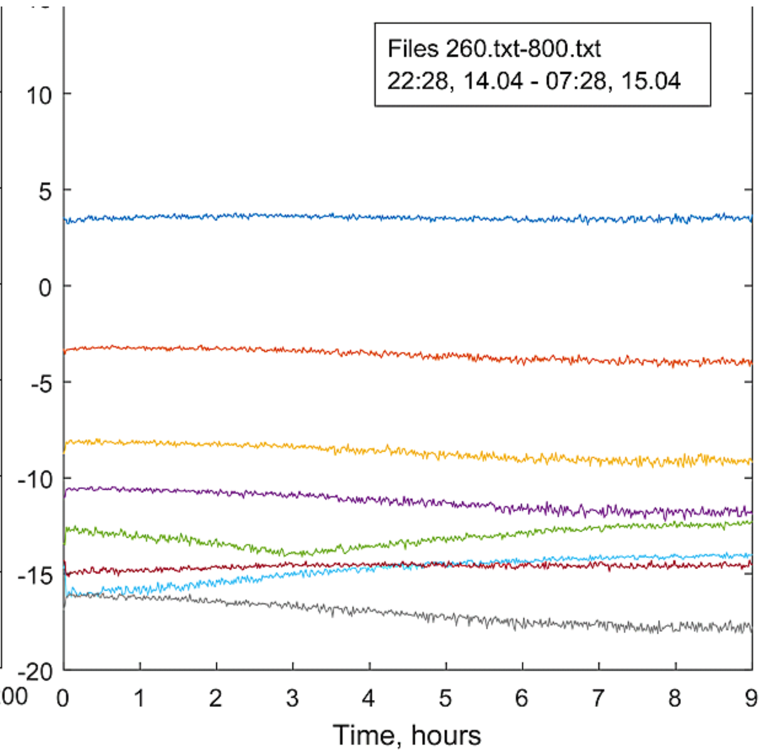
Same comb was existed over 30 hours!

Was most stable during the night.

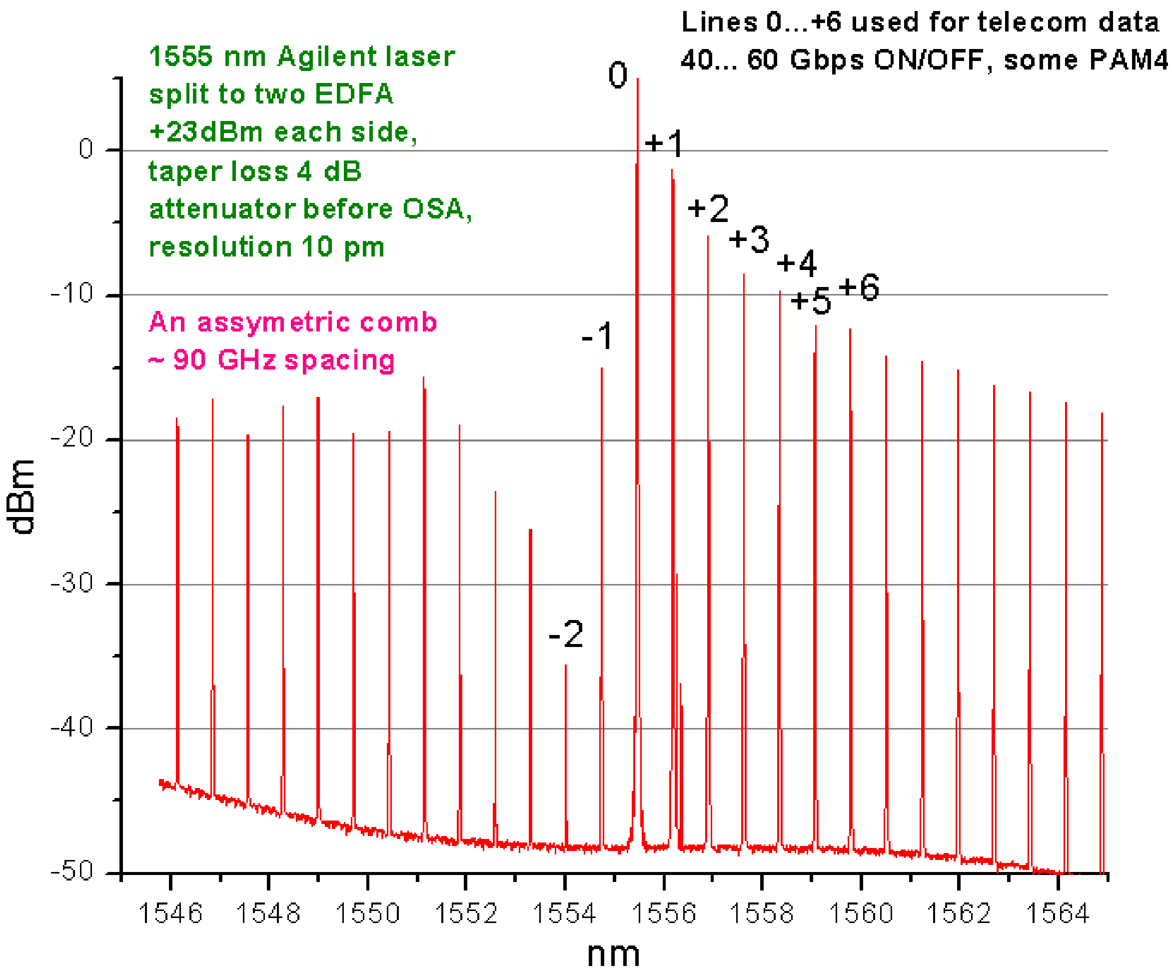








We put 40, 50, 60 Gbps and PAM4 on a filtered out single comb line and could transmit through 2 km fiber. We could use comb lines 0, +1, +2, +3, +4, +5, +6 for reasonable BER. BER deteriorated with weaker comb lines. If 6 comb lines were sent togather then there was a crosstalk between channels at 50 Gbps because presently our comb spacing is 89.5 GHz.



(0) 1555.450 +6.8 dbm, pump 23 dbm-taper 4 dbm= 19 dbm. Atttenuator 19-6.8=12.2 dbm

(+1) 1556.170 -1.2 + 12.2= 11dBm

(+2) 1556.892 -5.6 + 12.2= 6.6

(+3) 1557.612 -8.5 + 12.2= 3.7

(+4) 1558.346 -9.7 + 12.2= 2.5

(+5) 1559.060 -12 + 12.2= 0.2

(+6) 1559.782 -12.2 + 12.2= 0 dbm standard level for telecom

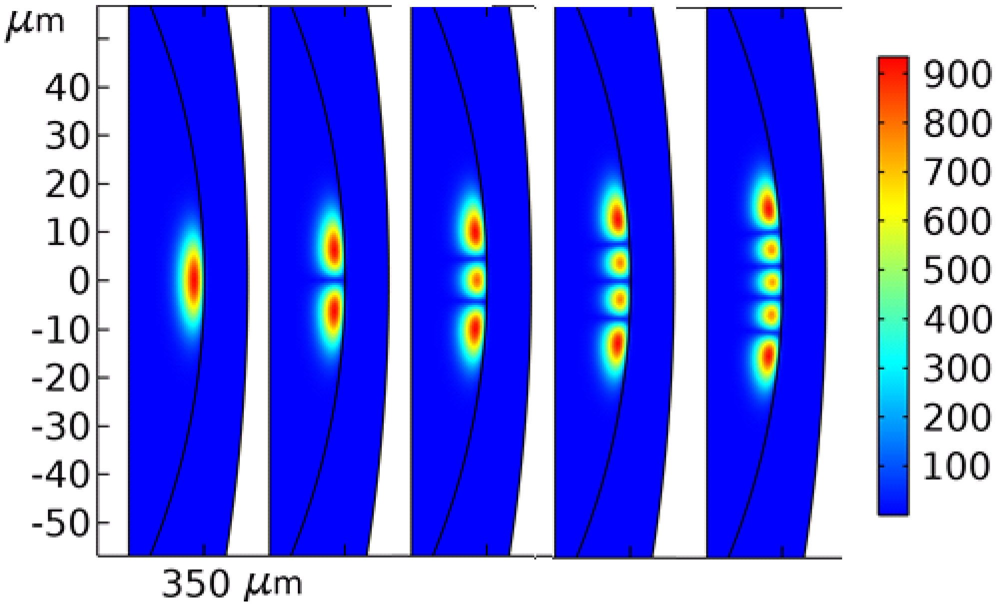
(+7) 1560.506 -14.2 _ 12.2= -2 dBm not good enough for fast telecom

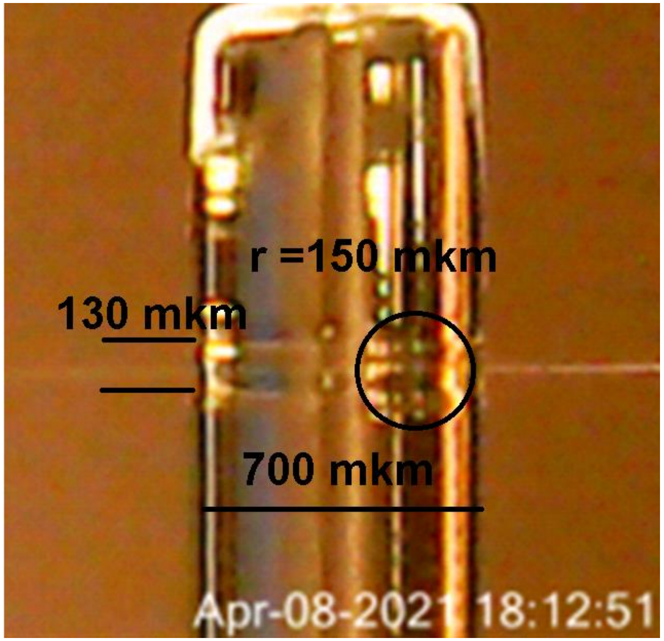
Вчера нам удалось добиться новых результатов, используя гребенку, выполняя общую передачу 0,5 ТБ / с с использованием гармоник (0; 1; 2; 3; 4), каждая гармоника 100 Гбит/с (50 Гбод/с PAM-4).

Requirements for telecom data transfer

- Discussion with Jurģis Porins and Sandis. Spolitis. Why telecom channel spacing is 100 GHz.
- If faster data speeds >100 GHz shorter pulses then would be problems with dispersion at long distances. Faster electronics > 100 GHz not available.
- 40 GHz data rates stayed as a standard for longer time.
- If channel separation 100 GHz, max data frequency 50 GHz - not always true, if compression is used then can compress data to 28 GHz window using a 4th order filter. Filter however introduces distortion in time.
- 40 Gbps is practical because should have a safety margin because DFB lasers used for channels have wavelength drifts.
- Comb lines are better because they are stricktly equidistant.
- Telecom is oriented on DFB lasers that have power 1 mW or 0 dBm, we should get comb lines this strong for fast data transfer.
- I remebered from 10 GHz microwave stuff that to measure above detector thermal nois e should use power not less than 1 mW.
- If we have more comb lines, the pump energy spreads over many lines and each line has smaller peak power.
- Comb output is short pulses that can be used for LIDAR. Could it cause nonlinearity problem in long fibers?
- Brillouin effect not a problem because pulses are too short to coause accoustic excitations.
- In fast speed communications Energy per bit 1 bit ~ 10 photons. There is never a strict line between error free transmission and mathematical probability is used described by BER.

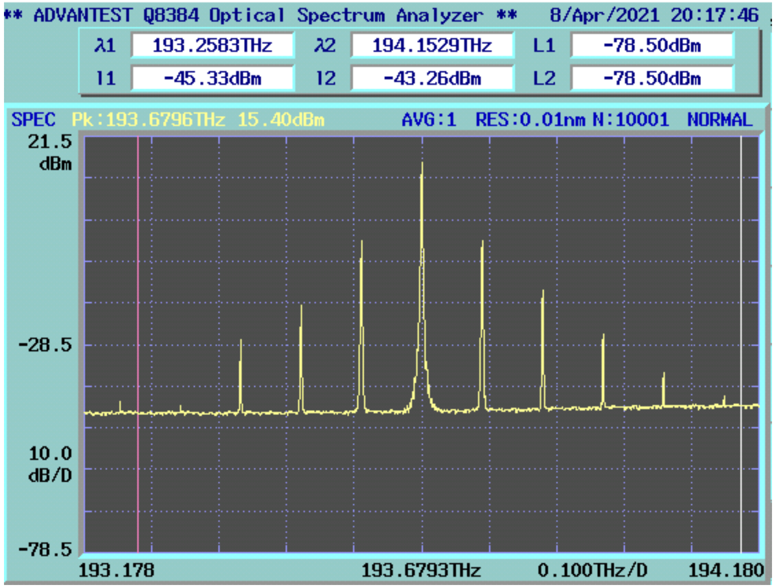
COMSOL Modes λ=1550nm, R=350μm, r=150μm

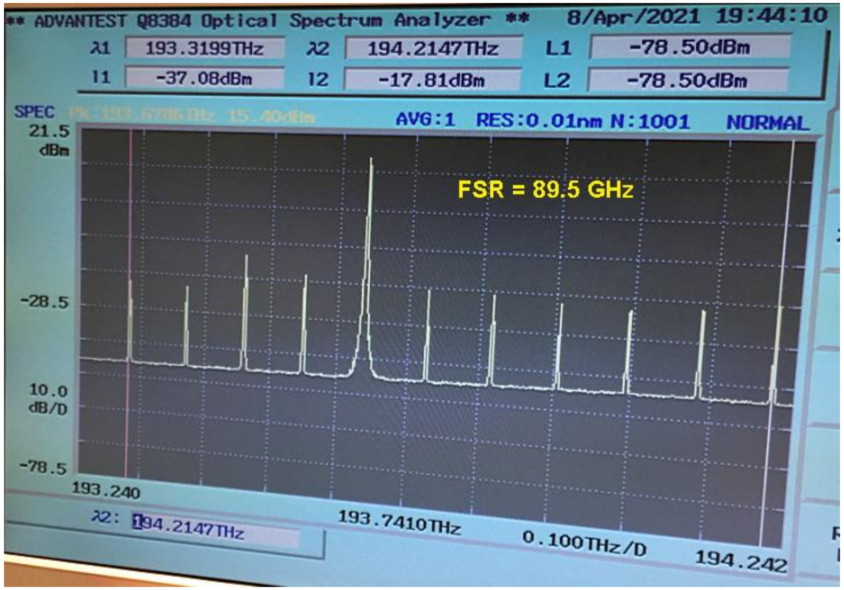




2021. 04.08. **MPL resonator nr 2 from top (Rod nr 8). FSR = 89.5 GHz.**

on the left is Turing rolls and on the right is modulation instability comb.





How would we know if we get a soliton comb?

- Would see a decrease of noise.
- Spectrum would have hyperbolic function envelope signature.