NACIONĀLAIS
ATTĪSTĪBAS
PLĀNS 2020

EIROPAS SAVIENĪBA
Eiropas Reģionālās
attīstības fonds

IEGULDĪJUMS TAVĀ NĀKOTNĒ

6. atskaite par posmu no 13.10.2021. līdz 13.05.2021.

Par Latvijas Universitātes projekta “**Uz čukstošās galerijas modas mikrorezonatora bāzes veidota optisko frekvenču ķemmes ģeneratora izstrāde un tā pielietojumi telekomunikacijās**” Nr. 1.1.1.1/18/A/155 **norisi**

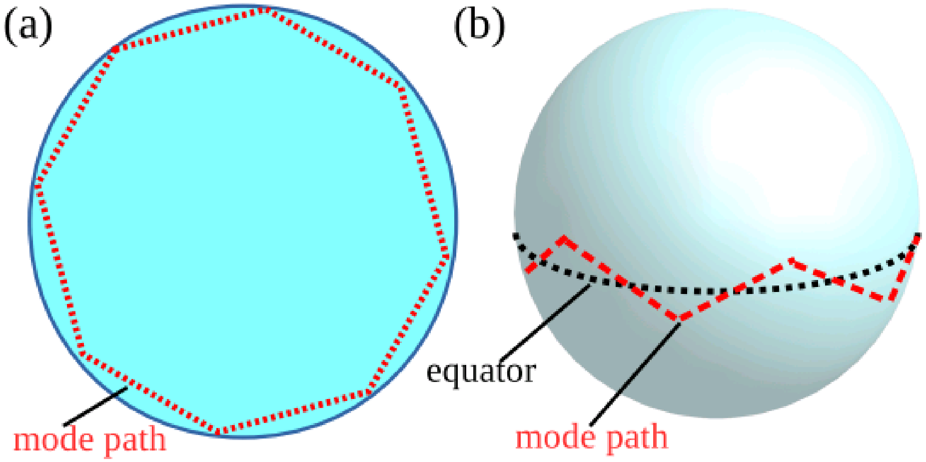
Projekta vispārējais mērķis: Veikt pētniecību, kas veicina Latvijas viedās specializācijas stratēģijas mērķu sasniegšanu, cilvēkkapitāla attīstību zinātnē un tehnoloģijās un jaunu zināšanu radīšanu, lai uzlabotu konkurētspēju tautsaimniecībā.

Projekta mērķis ir: iegūt jaunas zināšanas par čukstošo galeriju modu rezonatoru optiskajām frekvenču ķemmēm (WCOMBs) un izstrādāt, konstruēt un testēt ķemmes ģeneratora prototipu telekomunikāciju pielietojumiem.

Prezentēja: Jānis Alnis, MS Teams, LU ASI 2022. g. 3. maijā.

Whispering gallery microresonator basics

- Use total internal reflection
- Do not need mirror coatings
- Work in broad wavelength range
- Can be made in house
- Simple enough for Latvia
- Sensors, nonlinear optics



Optical quality factor Q

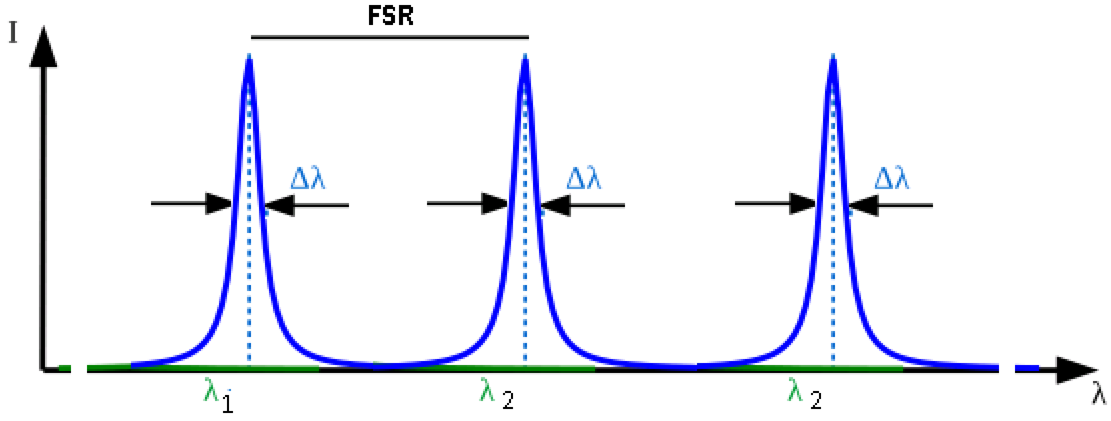
Q = ω τ,
where τ is the phton lifetime

Q = $\upsilon/\Delta\upsilon$= $\lambda/\Delta\lambda$,
where υ is the optical frequency
and $\Delta\upsilon$ is the linewidth

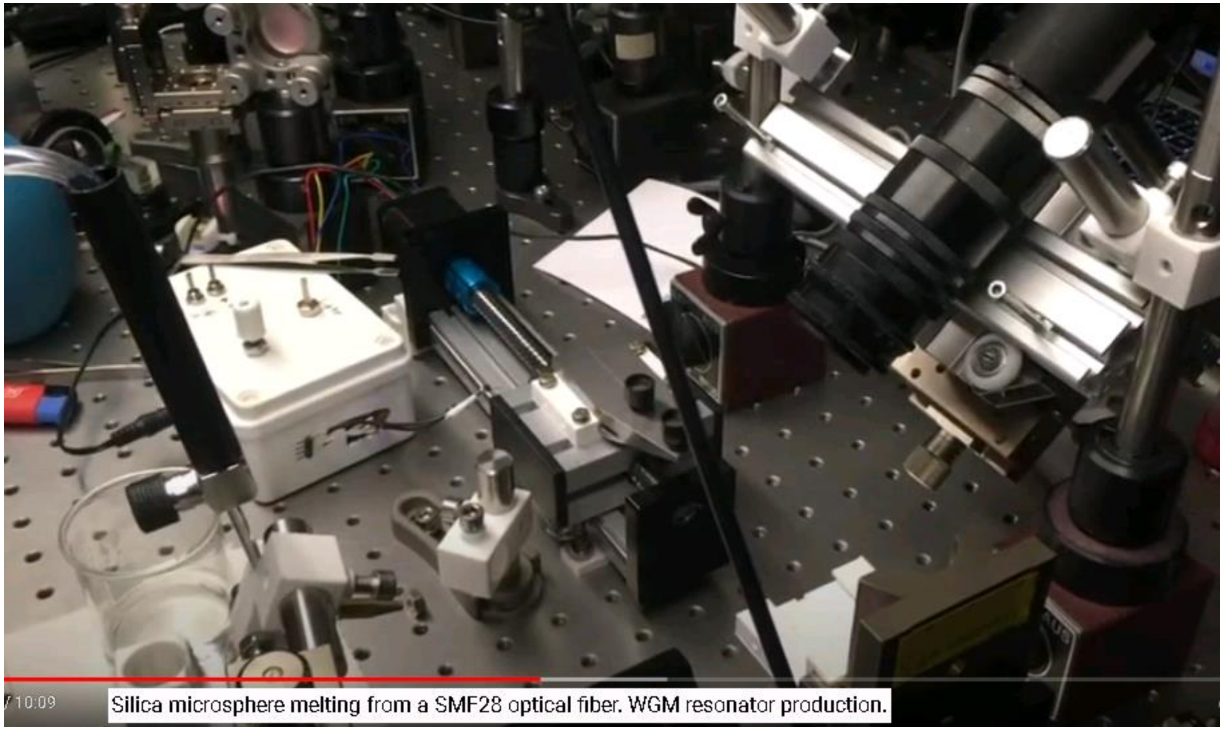
Q = 2π L / λ
where L is the photon path length.

Free spectral range:
FSR = c/2 **π** n R

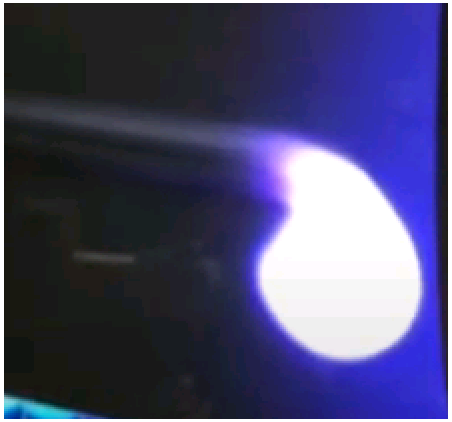
<u>Example:</u> 1mm sphere with Q factor 10^8. Light photons run 25 m inside untill decay due to scattering and absorption.

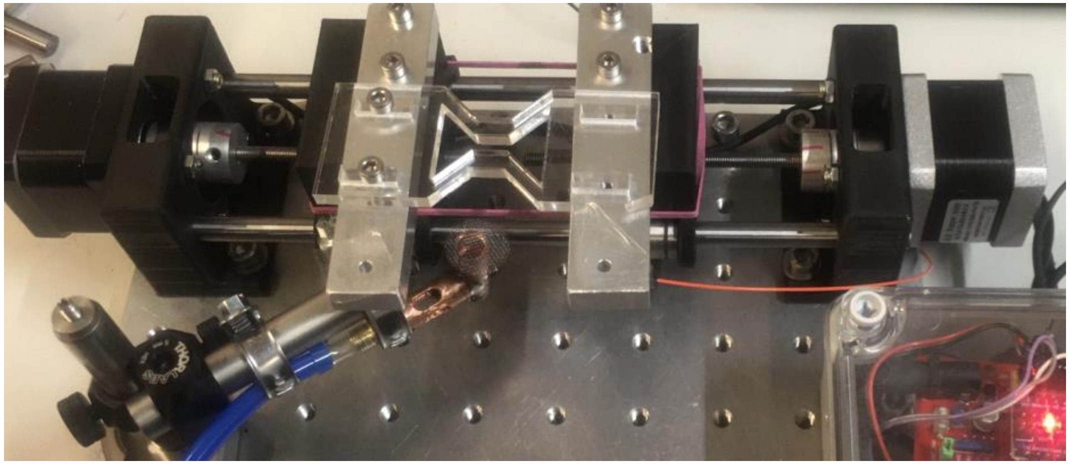


T1.1. Microsphere fabrication in ohy-hydrogen flame
T1.3. Tapered fiber pulling in pure hydrogen fllame



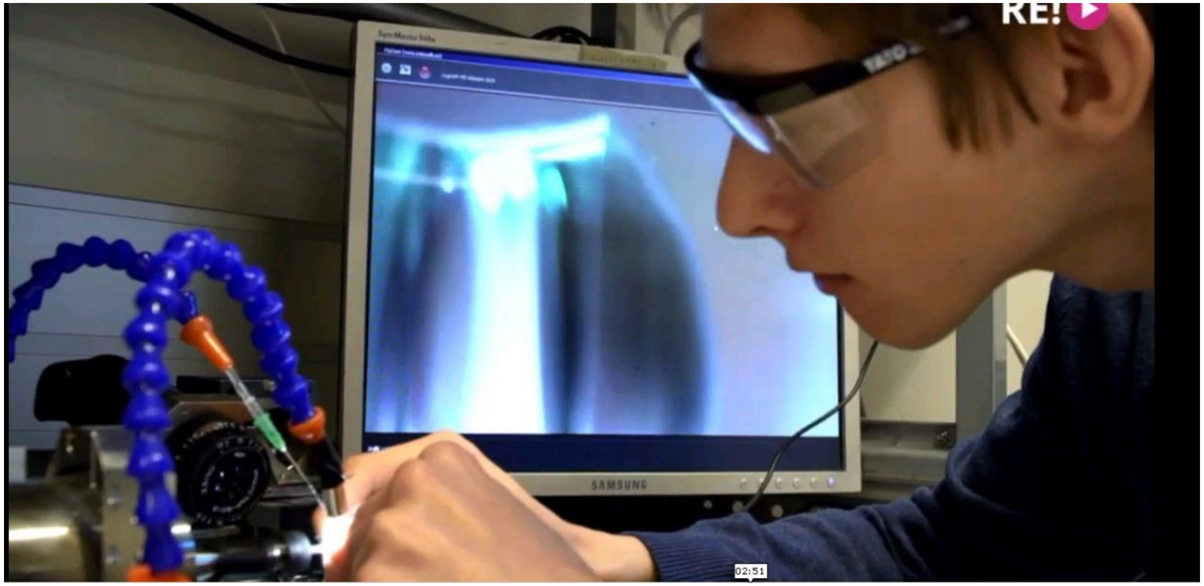
Silica microsphere melting from a SMF28 optical fiber. WGM resonator production.





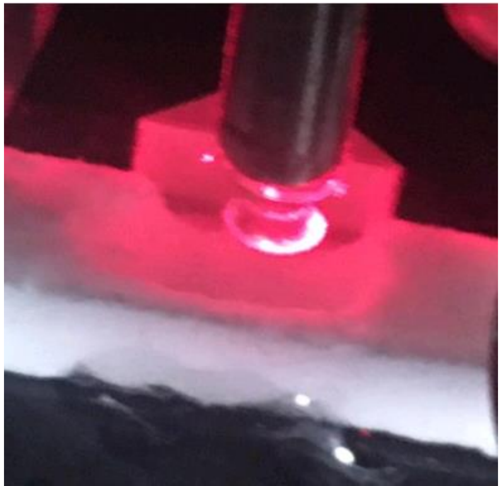
T1.1. Grinding and polishing of resonators with abrasives on air-bearing spindle. Disadvantage : time consuming!

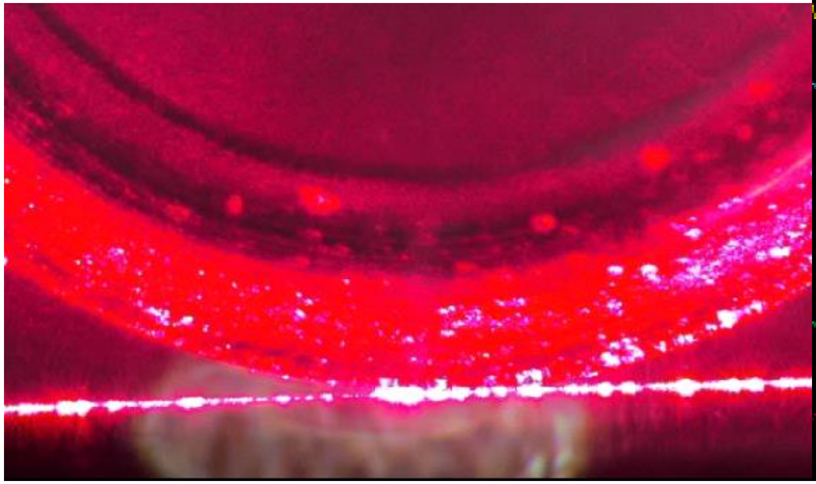
Materials CaF_2 , MgF_2 plexiglass, fused silica.

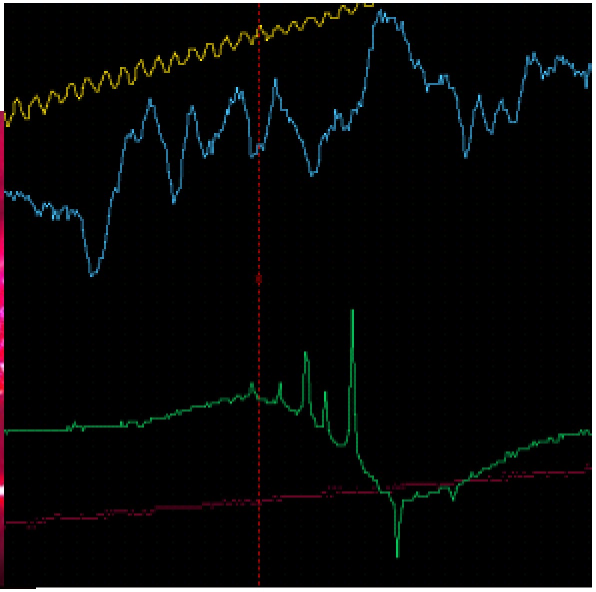


Diamond abrasives

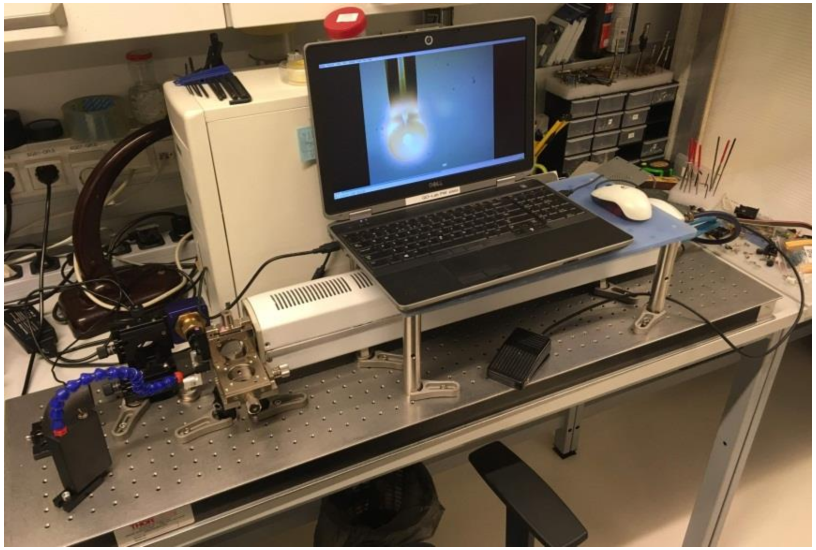
Prism and tapered fiber coupling resonances →

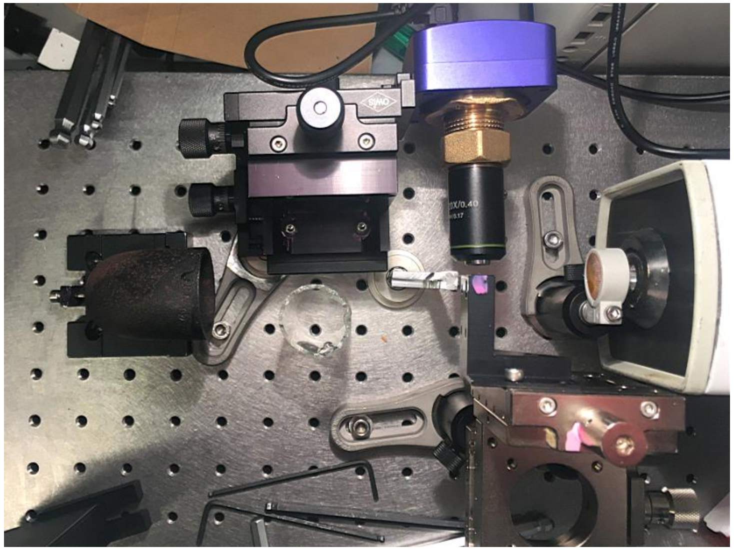






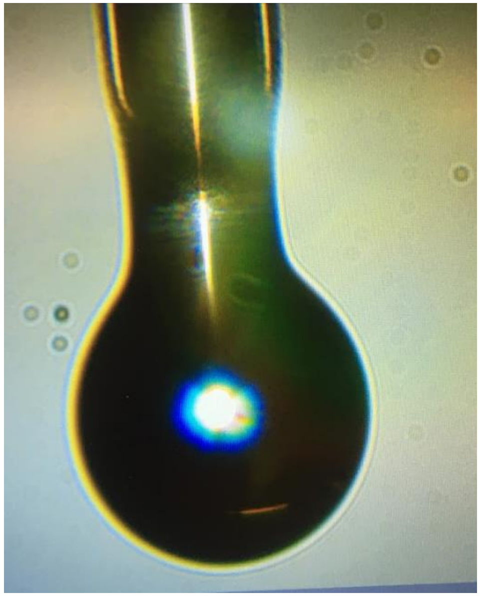
T1.1.Microsphere and microrod fabrication with a 40W CO_2 laser lathe. Most novel method. Needs in future motorised CNC control.

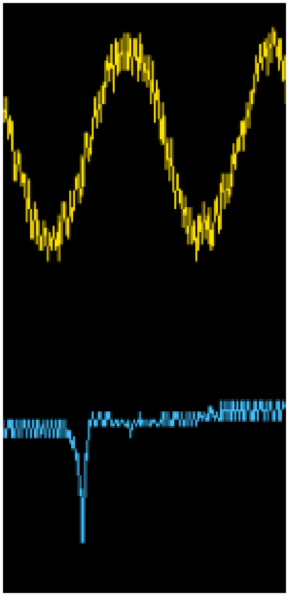




Home-made microscope: 20x objective from Ebay (60 EUR) and Astronomy webcam (150 EUR)

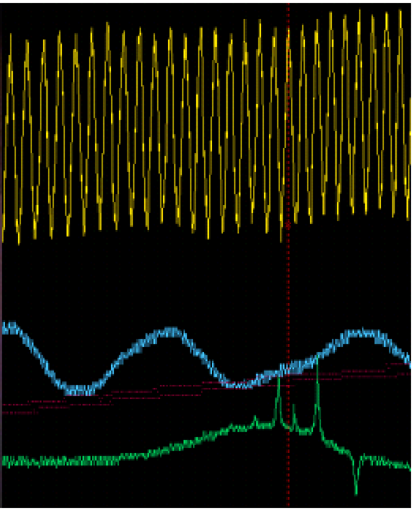
Sphere WGMR FWHM = 2 MHz **Q = 2E8 at 780 nm**



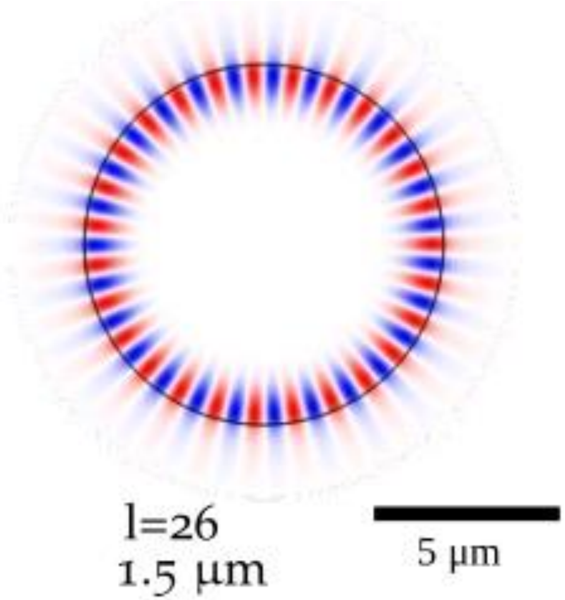


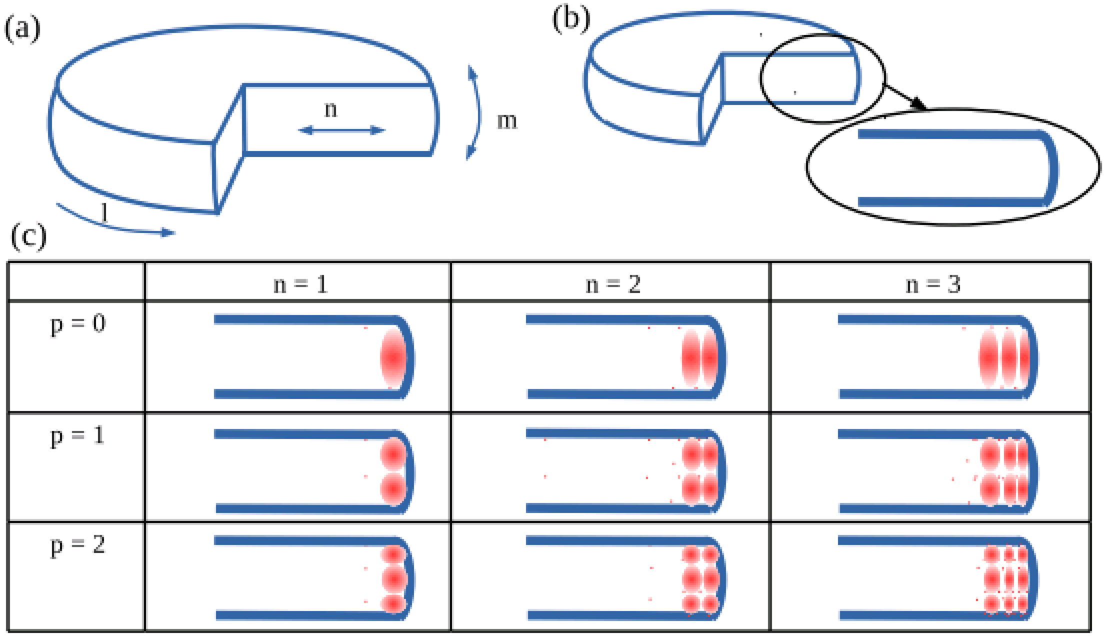
Yellow reference interference fringes from fiber etalon have 50 MHz period.

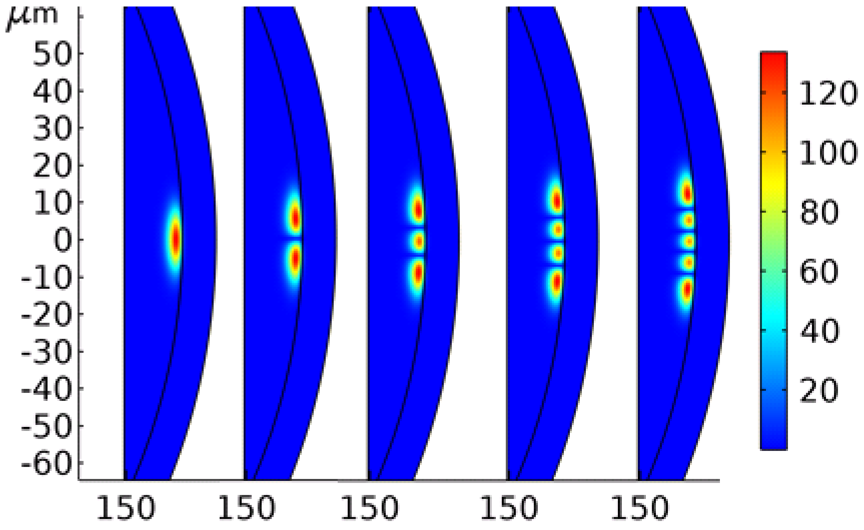
Microrod CO_2 lathe first resonances Q ~ 10^6. Evaporated silica dust is a problem



T1.4. Wave optics modeling of optical modes in COMSOL Multiphysics software



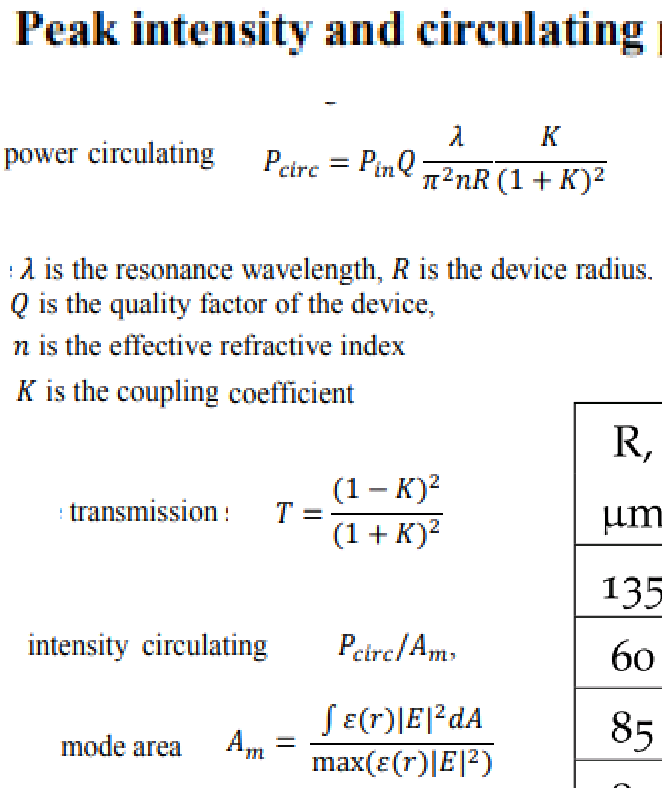




Understanding different WGMs: (a) radial mode number n, azimuthal mode number l and polar mode number m dirctions; (b) the region for plane sliced from a microsphere WGM resonator and (c) the intensity distributions for various modes in the slice.

Kerr effect - optical matrials slightly change their index of refraction at large light intensities.

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 device radius.
Q is the quality factor of the device,
n is the effective refractive index
K is the coupling coefficient

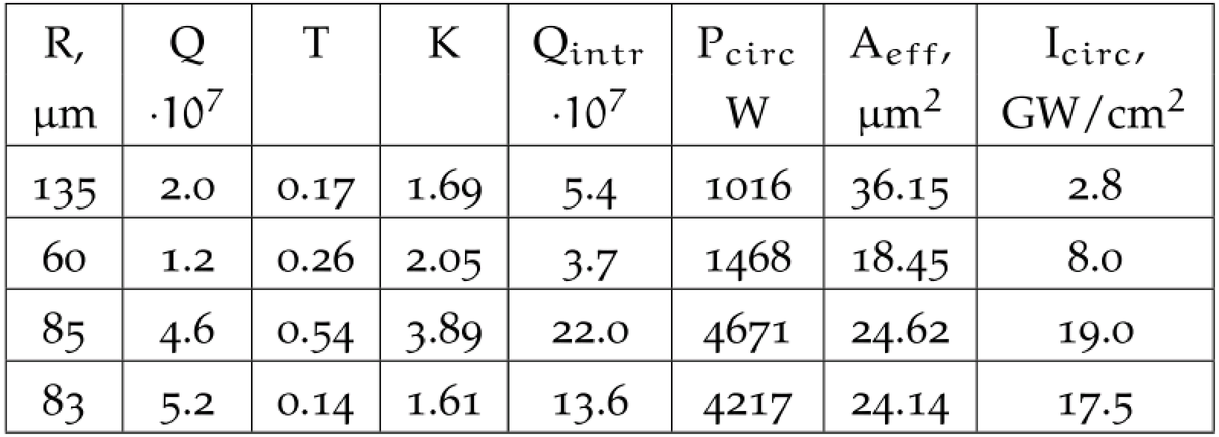
transmission: $T = \frac{(1-K)^2}{(1+K)^2}$

intensity circulating P_{circ}/A_m,

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

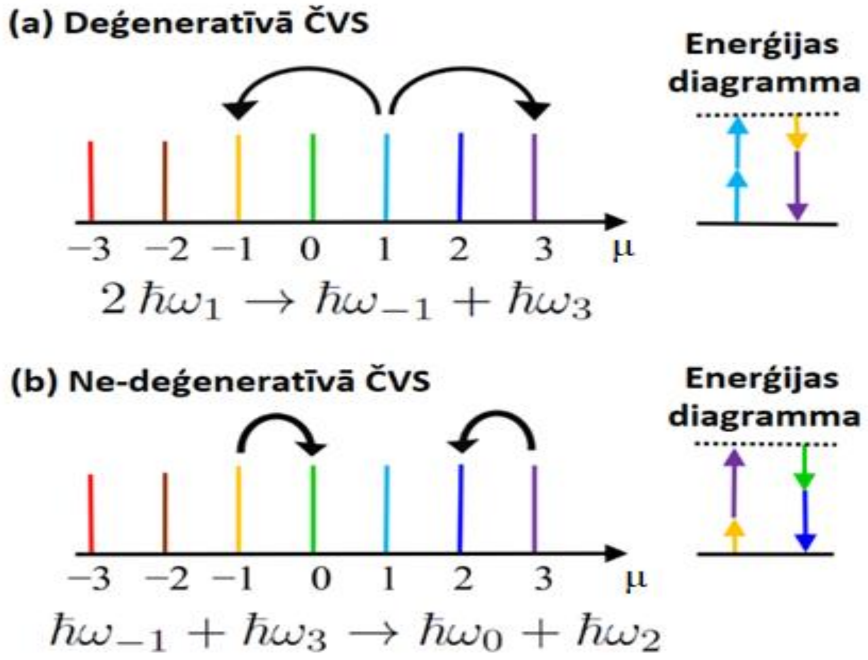
Mode areas *Aeff* obtained from Comsol simulation

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

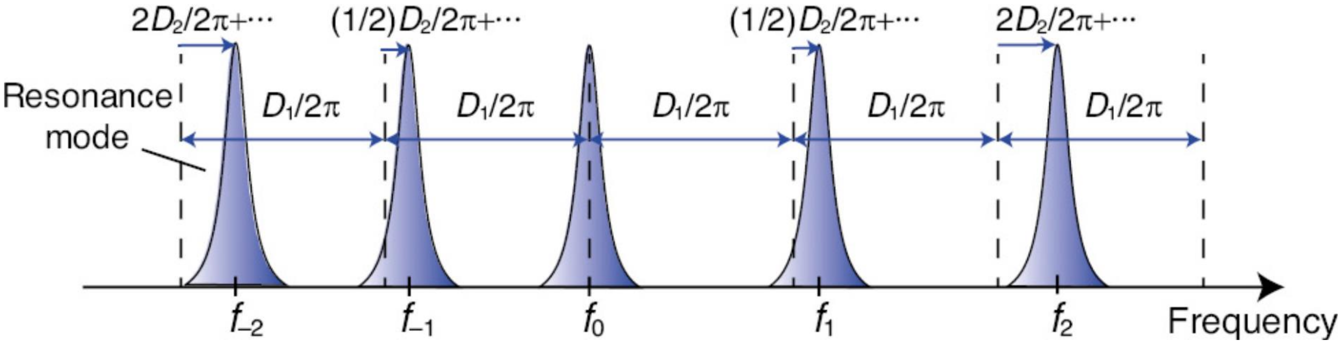


R, μm	Q $\cdot 10^7$	T	K	Q_{intr} $\cdot 10^7$	P_{circ} W	A_{eff}, μm^2	I_{circ}, GW/cm^2
135	2.0	0.17	1.69	5.4	1016	36.15	2.8
60	1.2	0.26	2.05	3.7	1468	18.45	8.0
85	4.6	0.54	3.89	22.0	4671	24.62	19.0
83	5.2	0.14	1.61	13.6	4217	24.14	17.5

Four Wave mixing (FWM) nonlinear process

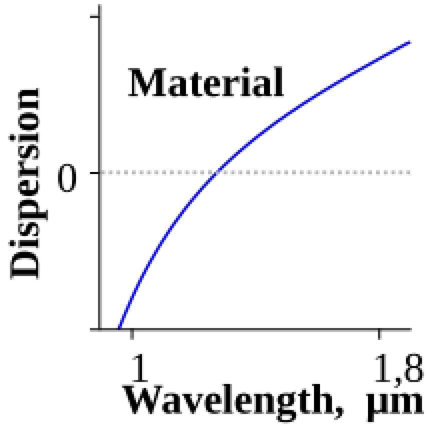


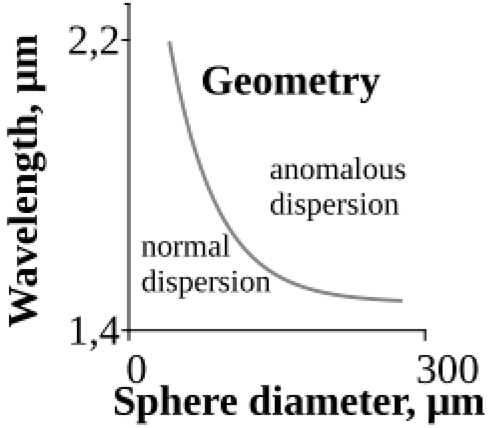
Dispersion caused detuning between comb and WGM lines

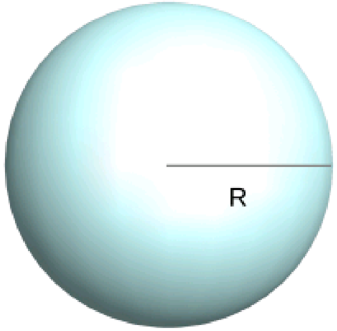


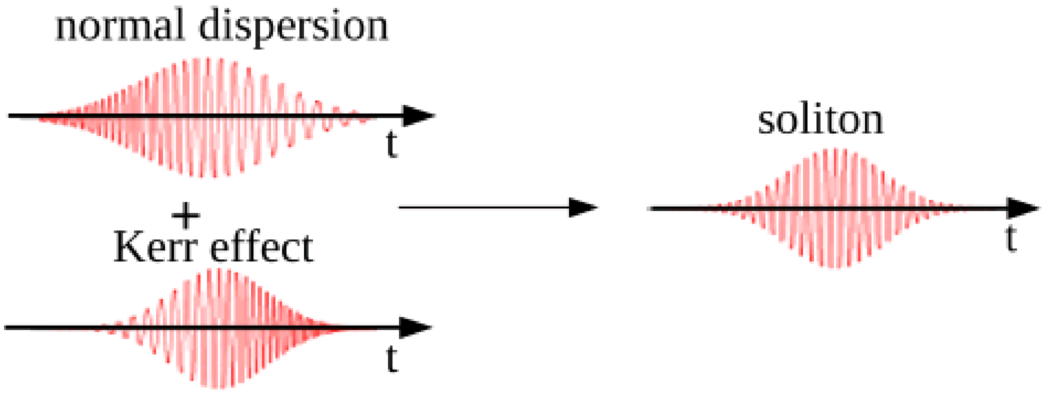
[S. Fujii, T. Tanabe, (2020) Dispersion engineering and measurement of whispering gallery mode microresonator for Kerr frequency comb generation, Nanophotonics 9, 1087–1104]

Material and geometrical dispersion depending on 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.

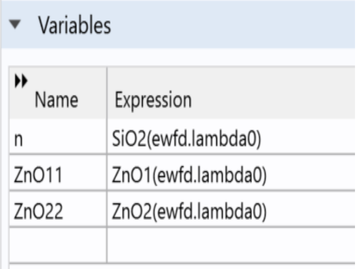
We have not been able to achieve soliton regime in microspheres because of microsphere heatup and the tunable laser that we have does not have large enough wavelength scan

COMSOL Multiphysics lietojums dispersijas aprēķināšanai

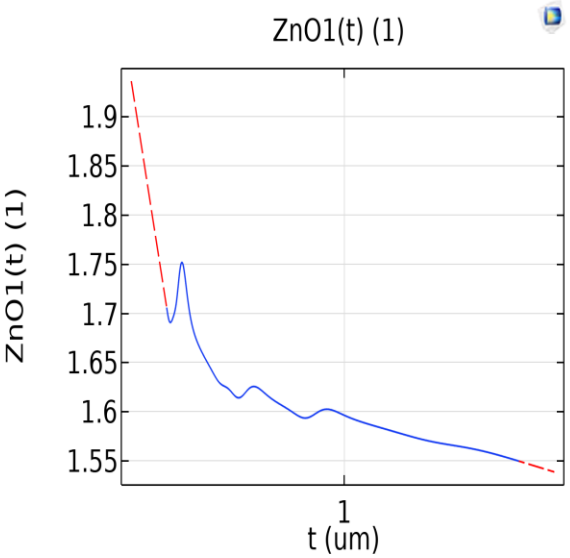
Rezonatora materiāla uzdošana

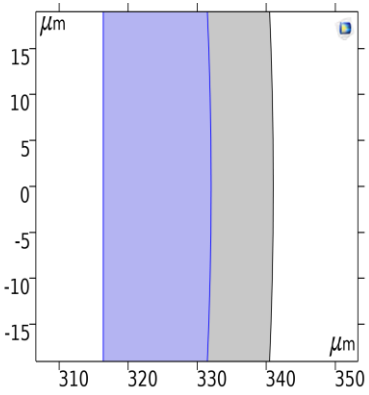
- Uzdod materiālās dispersijas datu tabulu
- Izveido interpulācijas funkciju *n*=*n*(λ)
- Uzdod materiāla apgabala gaismas laušanas koeficientu kā funkciju *n*(λ).

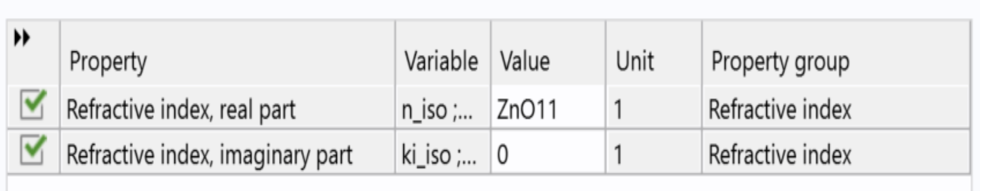
→ Rēķinot pie dažādām frekvencēm tiek ņemtas dažādas n vērtības



Name	Expression
n	SiO2(ewfd.lambda0)
ZnO11	ZnO1(ewfd.lambda0)
ZnO22	ZnO2(ewfd.lambda0)

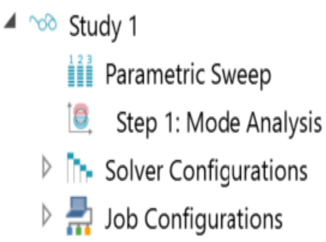




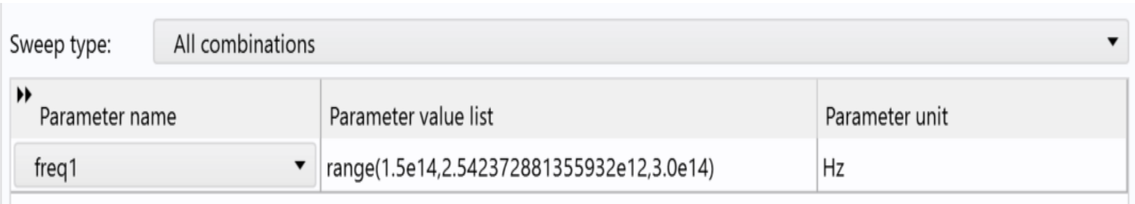


	Property	Variable	Value	Unit	Property group
☑	Refractive index, real part	n_iso ;...	ZnO11	1	Refractive index
☑	Refractive index, imaginary part	ki_iso ;...	0	1	Refractive index

Dispersijas aprēķins

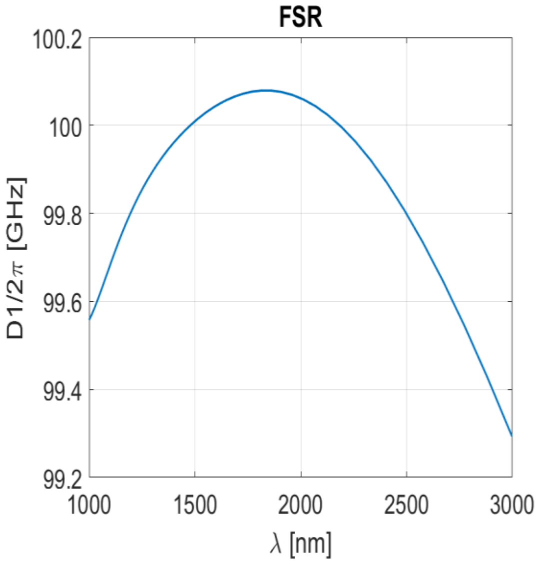


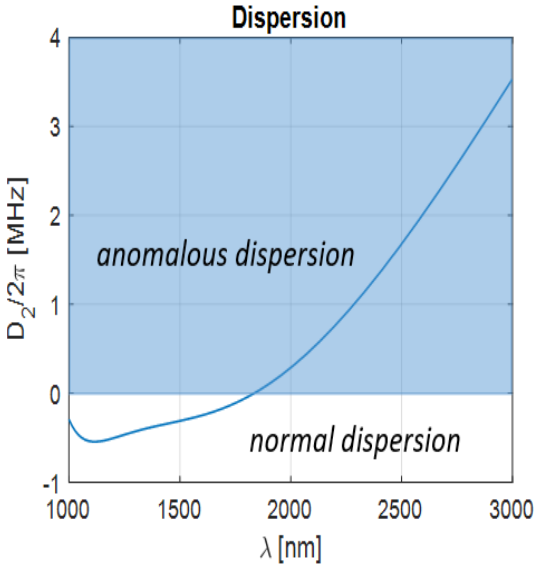
- COMSOL Multiphysics aprēķina n_{eff} izmantojot Mode Analysis
- Pēc formulas $2\pi R n = m\lambda$ aprēķina m
- MATLAB no tabulas uzdod $\omega = \omega(m)$ $[\mathrm{rad/s}]$
- Aprēķina $FSR = \frac{\frac{\partial\omega}{\partial m}}{2\pi}\ [Hz]$
- Dispersija $D_2 = \frac{\partial^2\omega}{\partial m^2}$ $[\mathrm{rad/s}]$



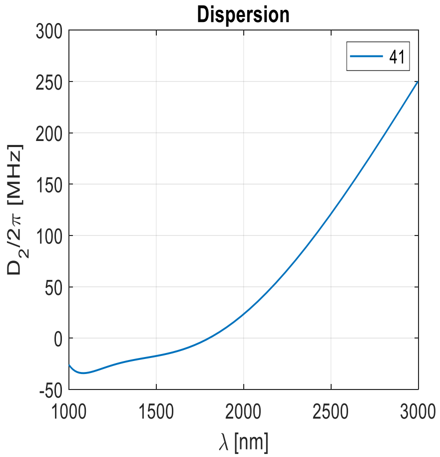
Sweep type: All combinations

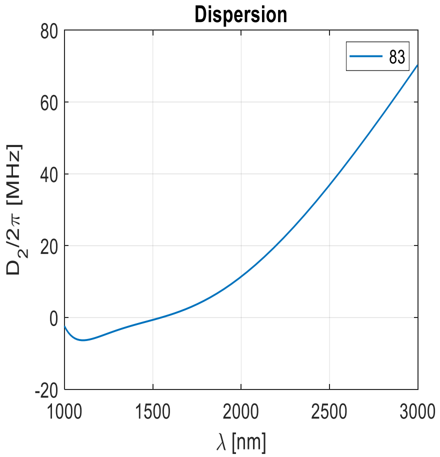
Parameter name	Parameter value list	Parameter unit
freq1	range(1.5e14,2.542372881355932e12,3.0e14)	Hz

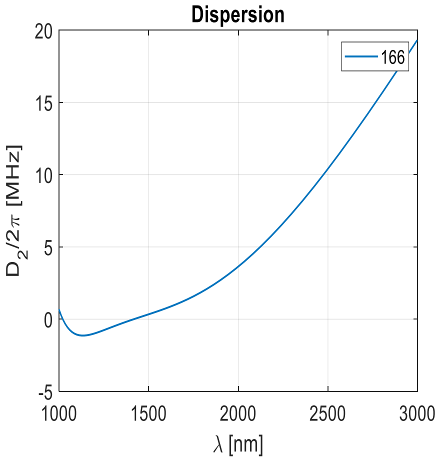


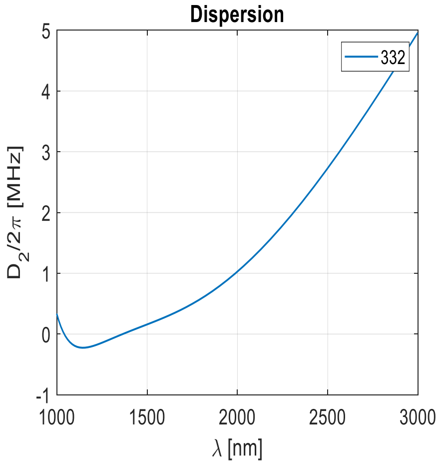


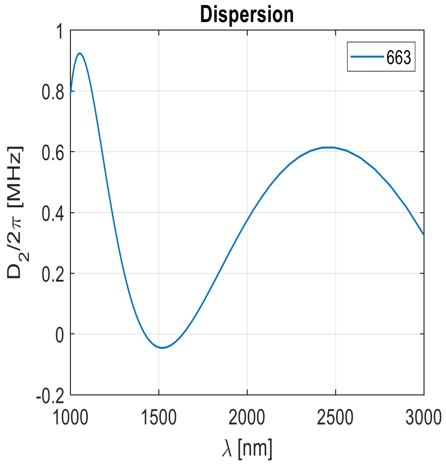
Nulles dispersijas viļņa garums dažādu izmēru SiO_2 sfērām







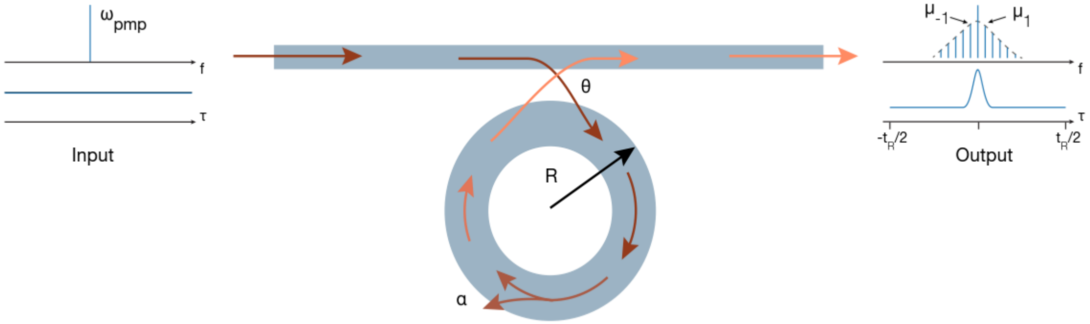




R, µm	FSR, GHz	ZDW, nm
41	800	1802
83	400	1545.6
166	200	1417.4
332	100	1041.3 & 1364.7
663	50	1421 & 1635

Lugiato-Lefevēra vienādojuma modelēšana

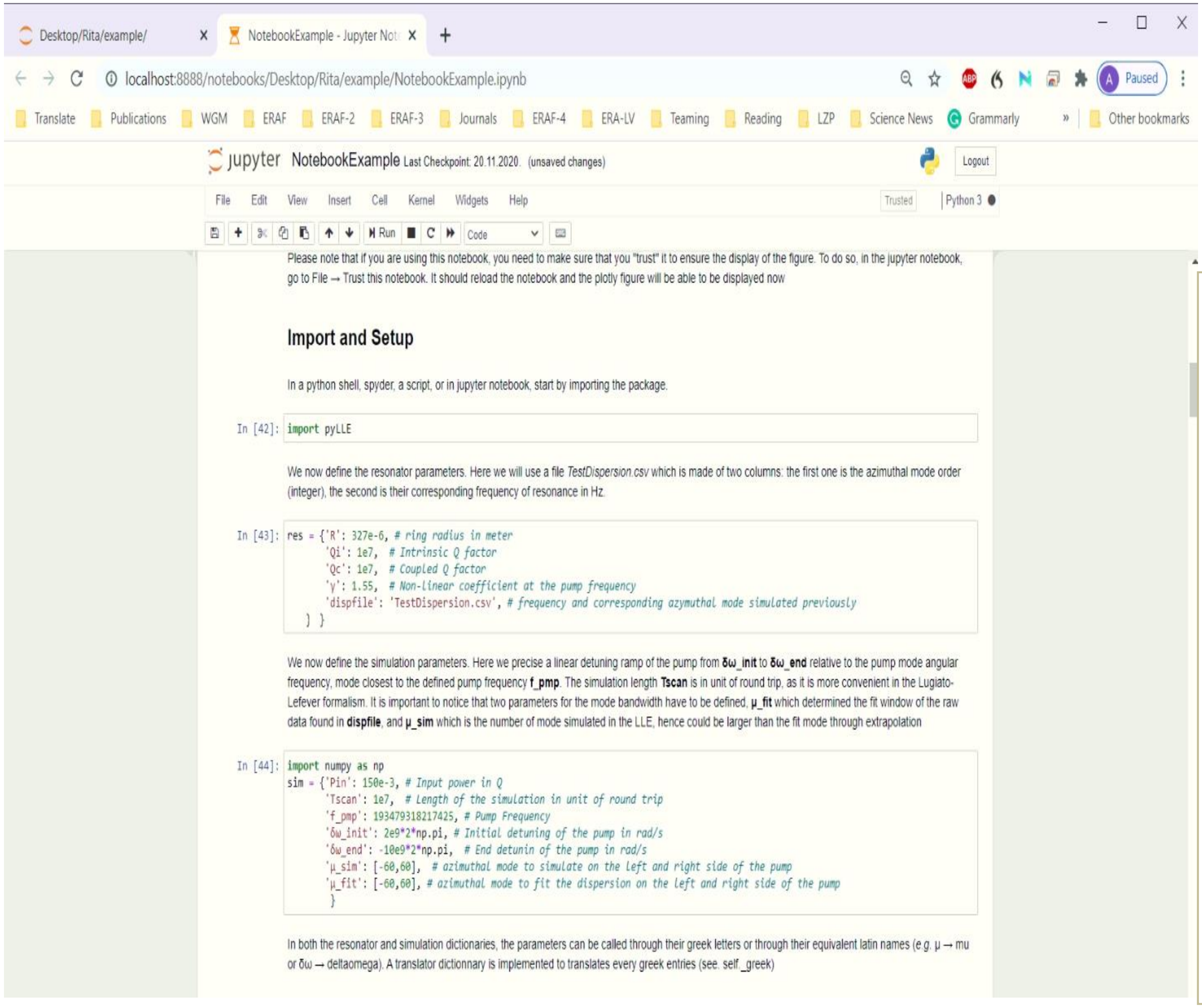
- Ar brīvpieejas programmatūru **pyLLE** (Python>3.4, Julia 0.6.4)
- [Moille G, Li Q, Lu X, Srinivasan K (2019) pyLLE: A Fast and User Friendly Lugiato-Lefever Equation Solver. J Res Natl Inst Stan 124:124012. https://doi.org/10.6028/jres.124.012.]



$$t_R\frac{\partial E(t,\tau)}{\partial t}=-\left(\frac{\alpha'}{2}-i\delta_0\right)E+i\cdot\mathrm{FT}^{-1}\left[-t_R D_{int}(\omega)\cdot\mathrm{FT}\left[E(t,\tau)\right]\right]+\gamma L|E|^2E+\sqrt{\theta}E_{in}$$

- kur integrālā dispersija ir $D_{int}=\omega_\mu-(\omega_0+D_1\mu)$

pyLLE



Please note that if you are using this notebook, you need to make sure that you "trust" it to ensure the display of the figure. To do so, in the jupyter notebook, go to File → Trust this notebook. It should reload the notebook and the plotly figure will be able to be displayed now

Import and Setup

In a python shell, spyder, a script, or in jupyter notebook, start by importing the package.

In [42]:
```
import pyLLE
```

We now define the resonator parameters. Here we will use a file *TestDispersion.csv* which is made of two columns: the first one is the azimuthal mode order (integer), the second is their corresponding frequency of resonance in Hz.

In [43]:
```
res = {'R': 327e-6, # ring radius in meter
       'Qi': 1e7,  # Intrinsic Q factor
       'Qc': 1e7,  # Coupled Q factor
       'γ': 1.55,  # Non-linear coefficient at the pump frequency
       'dispfile': 'TestDispersion.csv', # frequency and corresponding azymuthal mode simulated previously
   } }
```

We now define the simulation parameters. Here we precise a linear detuning ramp of the pump from **δω_init** to **δω_end** relative to the pump mode angular frequency, mode closest to the defined pump frequency **f_pmp**. The simulation length **Tscan** is in unit of round trip, as it is more convenient in the Lugiato-Lefever formalism. It is important to notice that two parameters for the mode bandwidth have to be defined, **μ_fit** which determined the fit window of the raw data found in **dispfile**, and **μ_sim** which is the number of mode simulated in the LLE, hence could be larger than the fit mode through extrapolation

In [44]:
```
import numpy as np
sim = {'Pin': 150e-3, # Input power in Q
       'Tscan': 1e7,  # Length of the simulation in unit of round trip
       'f_pmp': 193479318217425, # Pump Frequency
       'δω_init': 2e9*2*np.pi, # Initial detuning of the pump in rad/s
       'δω_end': -10e9*2*np.pi,  # End detunin of the pump in rad/s
       'μ_sim': [-60,60],  # azimuthal mode to simulate on the left and right side of the pump
       'μ_fit': [-60,60], # azimuthal mode to fit the dispersion on the left and right side of the pump
        }
```

In both the resonator and simulation dictionaries, the parameters can be called through their greek letters or through their equivalent latin names (*e.g.* μ → mu or δω → deltaomega). A translator dictionnary is implemented to translates every greek entries (see. self._greek)

Simulation Parameters:

R = 327.00 μm
Qi = 10.00 M
Qc = 10.00 M
γ = 1.55

Pin = 150.00 mW
Tscan = 10.00 x1e6 Round Trip
f_pmp = 193.48 THz
δω_init = 2.00 x2π GHz
δω_end = -10.00 x2π GHz
μ_sim = [-40.00,40.00]
μ_fit = [-40.00,40.00]

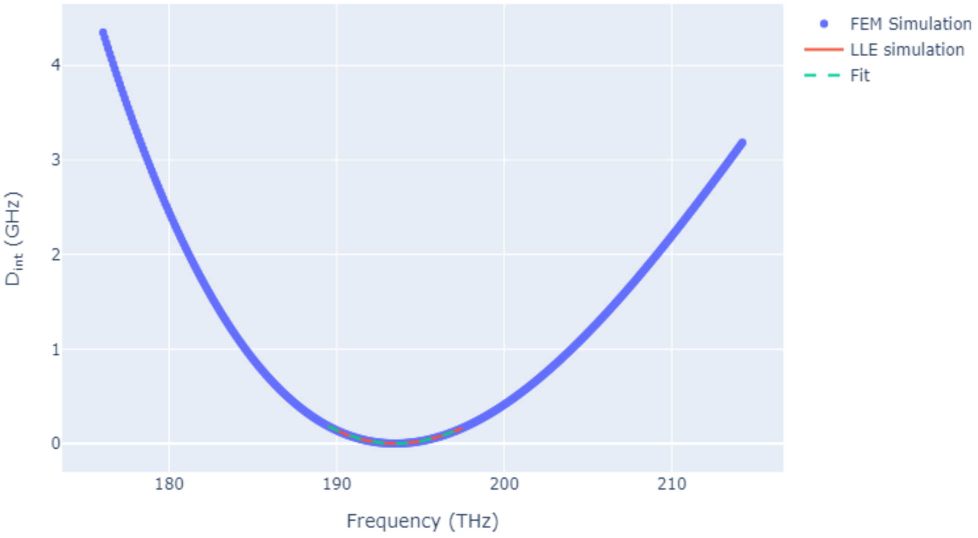
pyLLE

- Programmā tiek ielikts iepriekš, citur aprēķināts atbilstošā rezonatora modu un frekvenču lielumus, piemēram ar Sellmeiera vienādojumi:

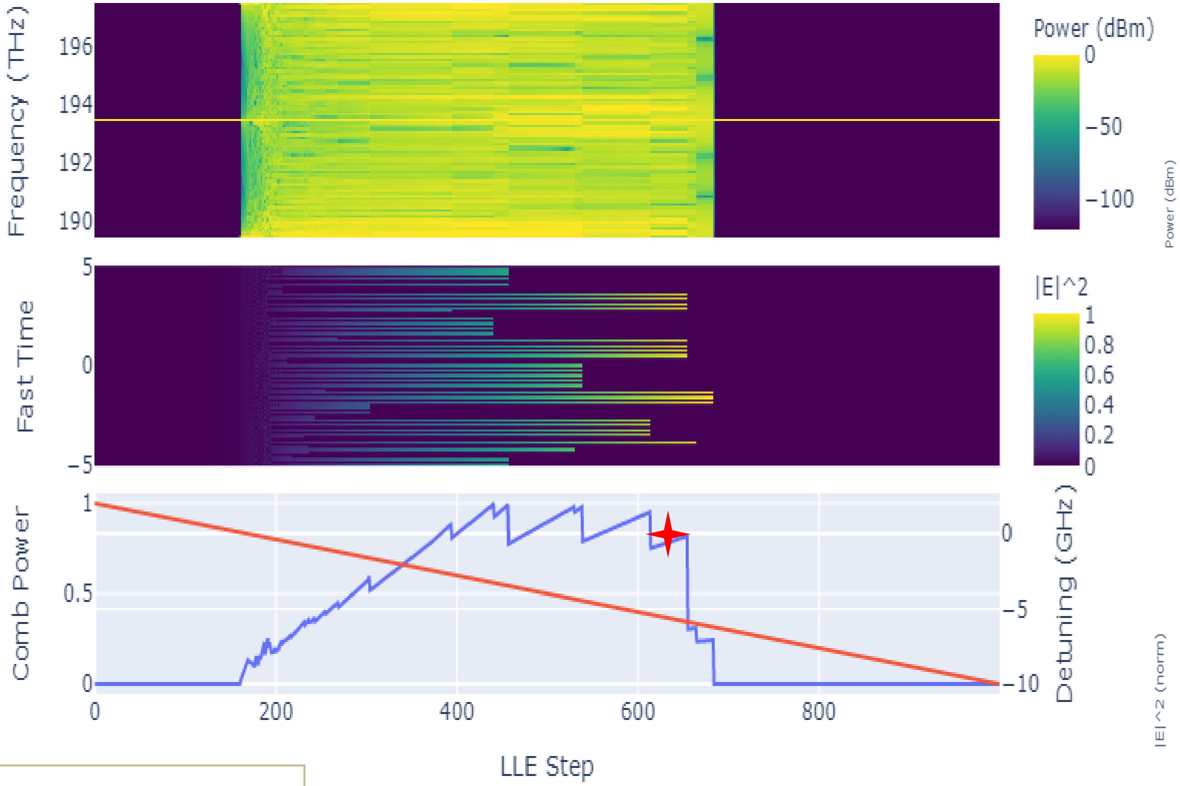
$$\lambda_{TE} \approx \frac{2\pi R n_1}{m + 1.856 m^{\frac{1}{3}} + \left(\frac{1}{2} - \frac{n_1}{\sqrt{n_1^2 - 1}}\right)}$$

$$n^2(\lambda) = 1 + \sum_i \frac{A_i \cdot \lambda^2}{\lambda^2 - B_i^2},$$

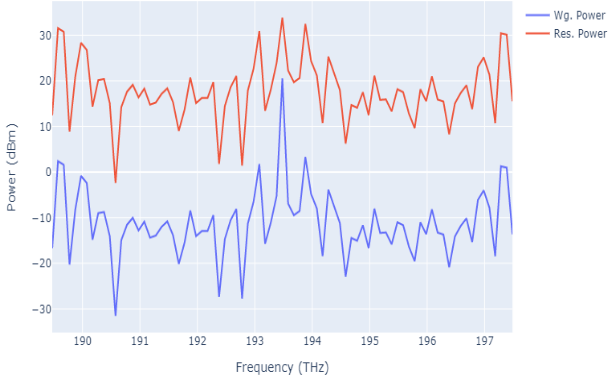
- Tiek aprēķināta integrālā dispersija

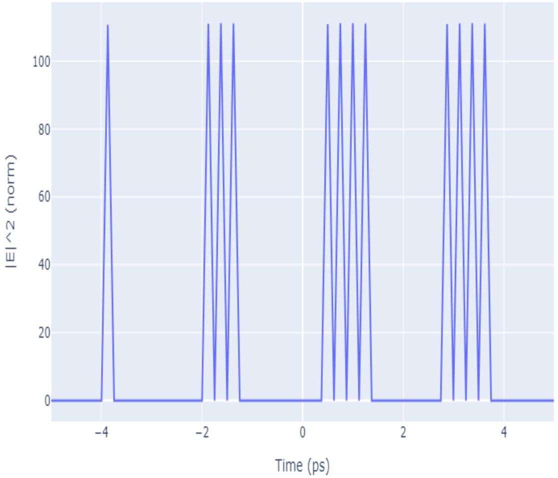


pyLLE – rezultātā iegūstam mikroķemmes uzvedību kā spektru, frekvenču ķemmes jaudu rezonatorā pie dažādiem LLE soļiem, kā arī pie noteiktiem soļiem redzam rezonatora elektriskā lauka spektru un sadalījumu laikā.



ind=630



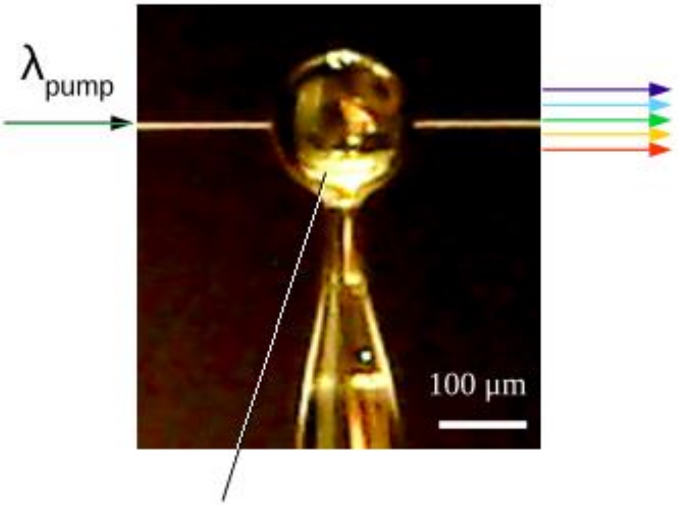


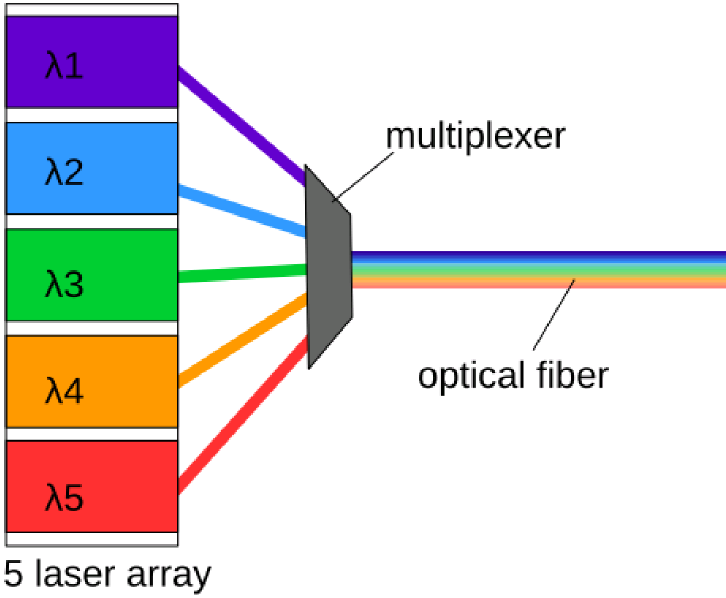
R = 327.00 µm
Q = 10.00 M
µ = [-40.00,40.00]
Center Pump: 193.479 THz
FSR: 100.15 GHz

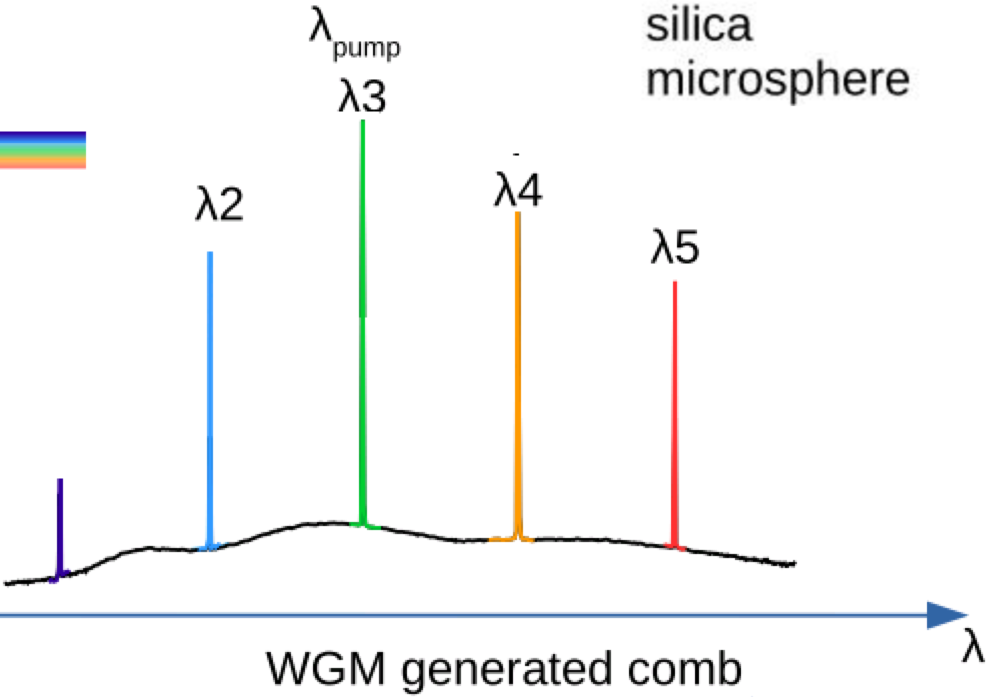
Future Vision of the Project outcome

Wavelength Division Multiplexing

Replace laser array with frequency comb generated inside WGM resonator.

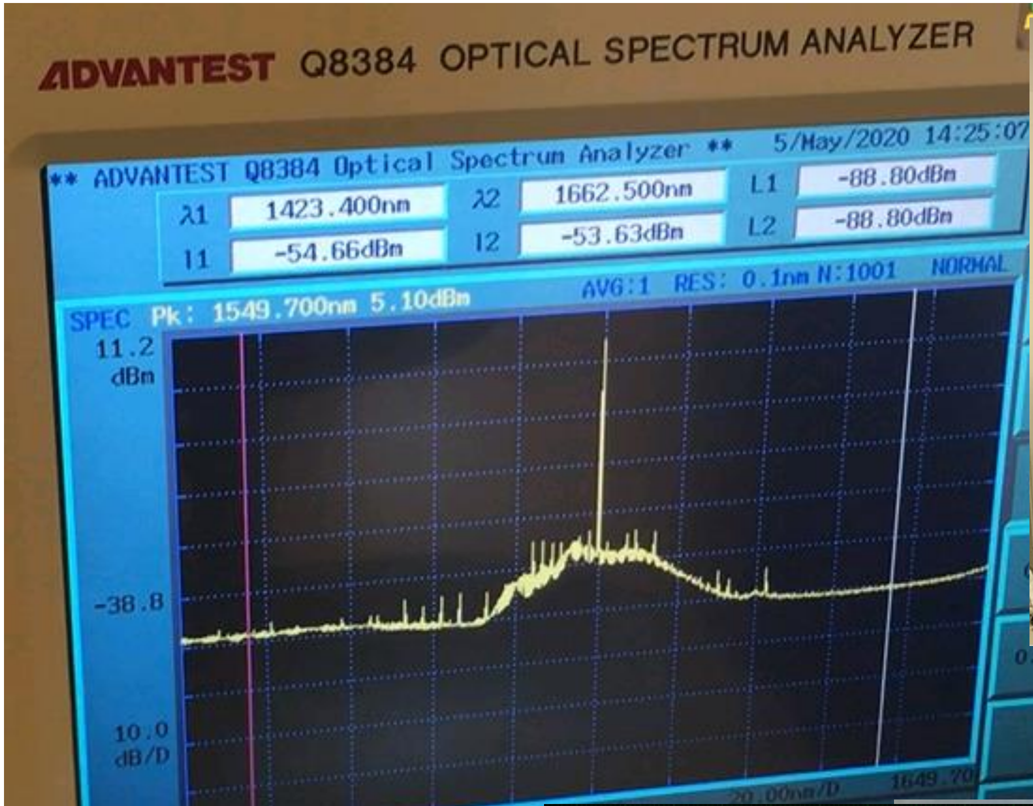






T1.3. May 2020. Our first comb from SiO_2 microsphere.

Weak and unstable in time because microsphere symmetry was deformed



** ADVANTEST Q8384 Optical Spectrum Analyzer ** 5/May/2020 14:25:07

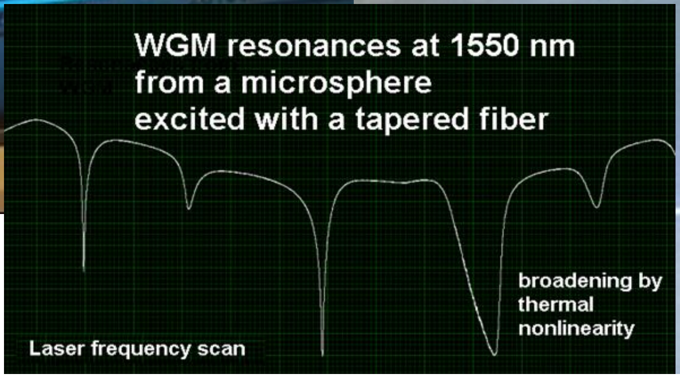
λ1 1423.400nm λ2 1662.500nm L1 -88.80dBm

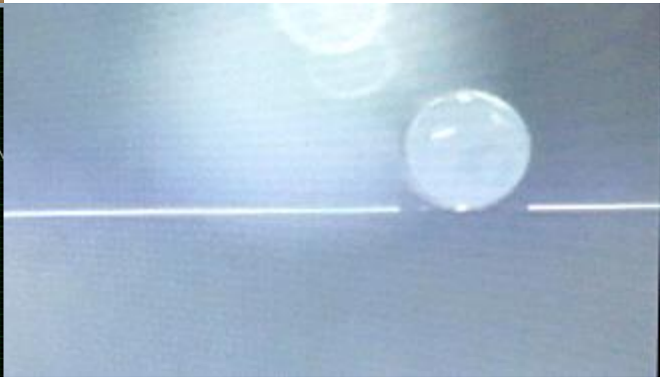
l1 -54.66dBm l2 -53.63dBm L2 -88.80dBm

AVG:1 RES: 0.1nm N:1001 NORMAL

SPEC Pk: 1549.700nm 5.10dBm

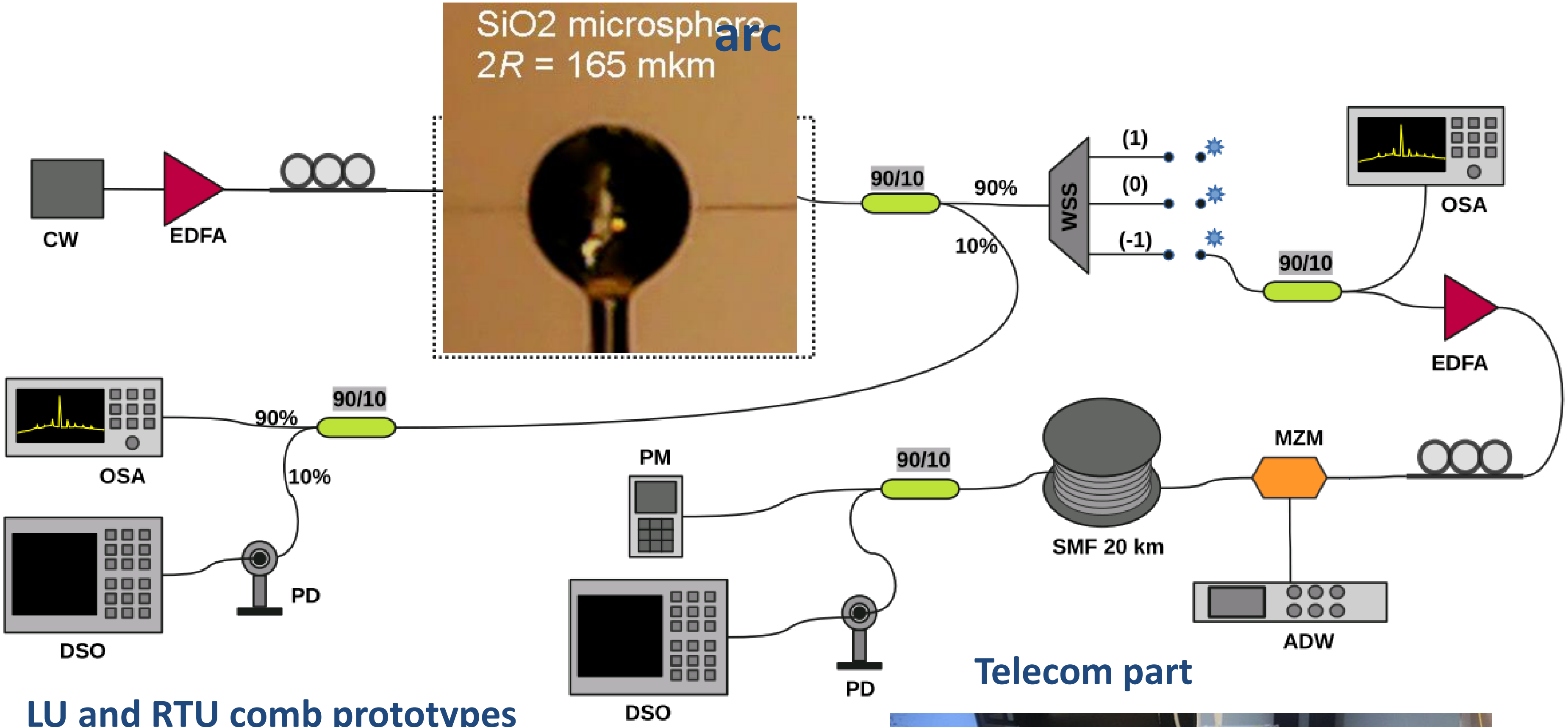
RESOLUTION: 0.1nm



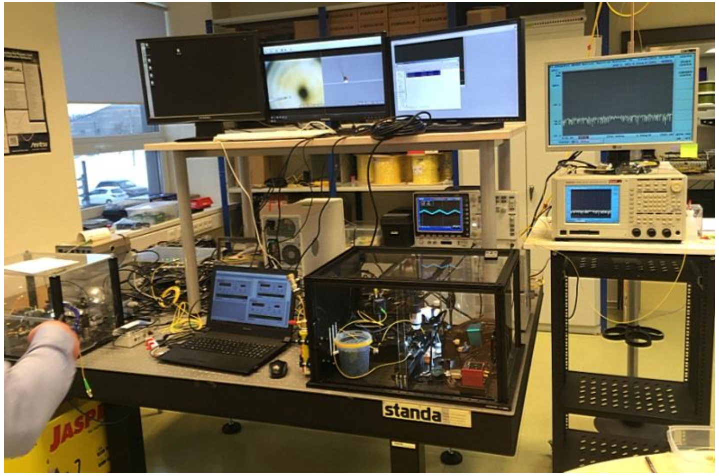


$Q \approx 3 \times 10^7$

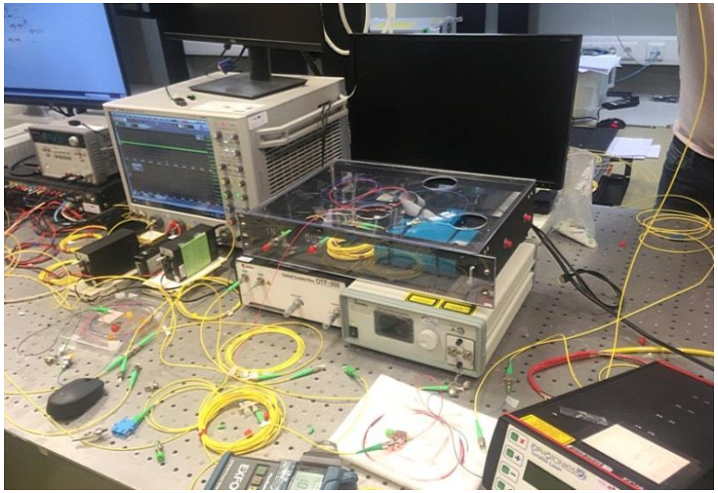
T2.1. Comb for telecom using round microsphere made in electric arc



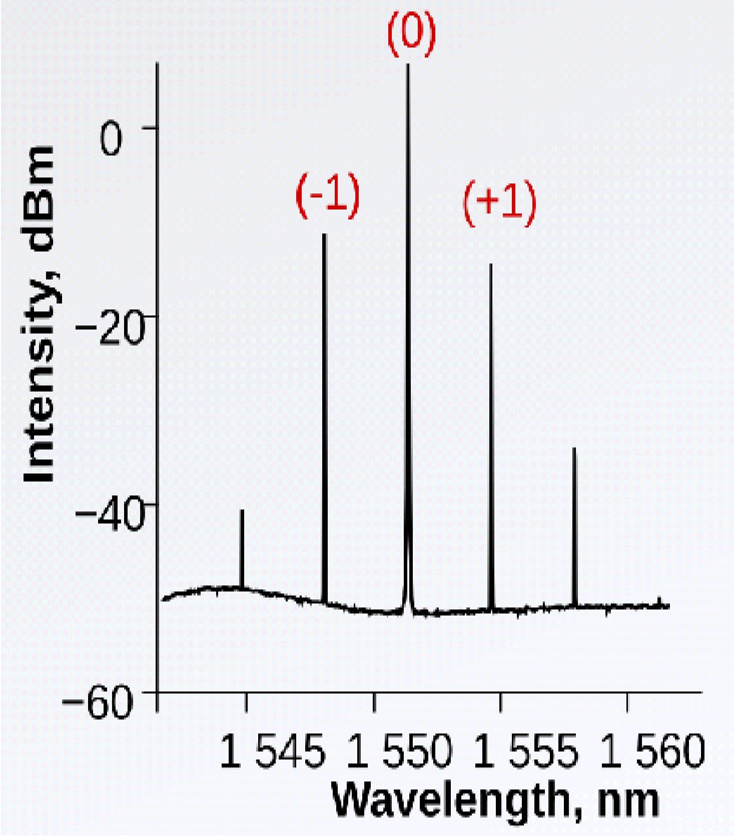
LU and RTU comb prototypes



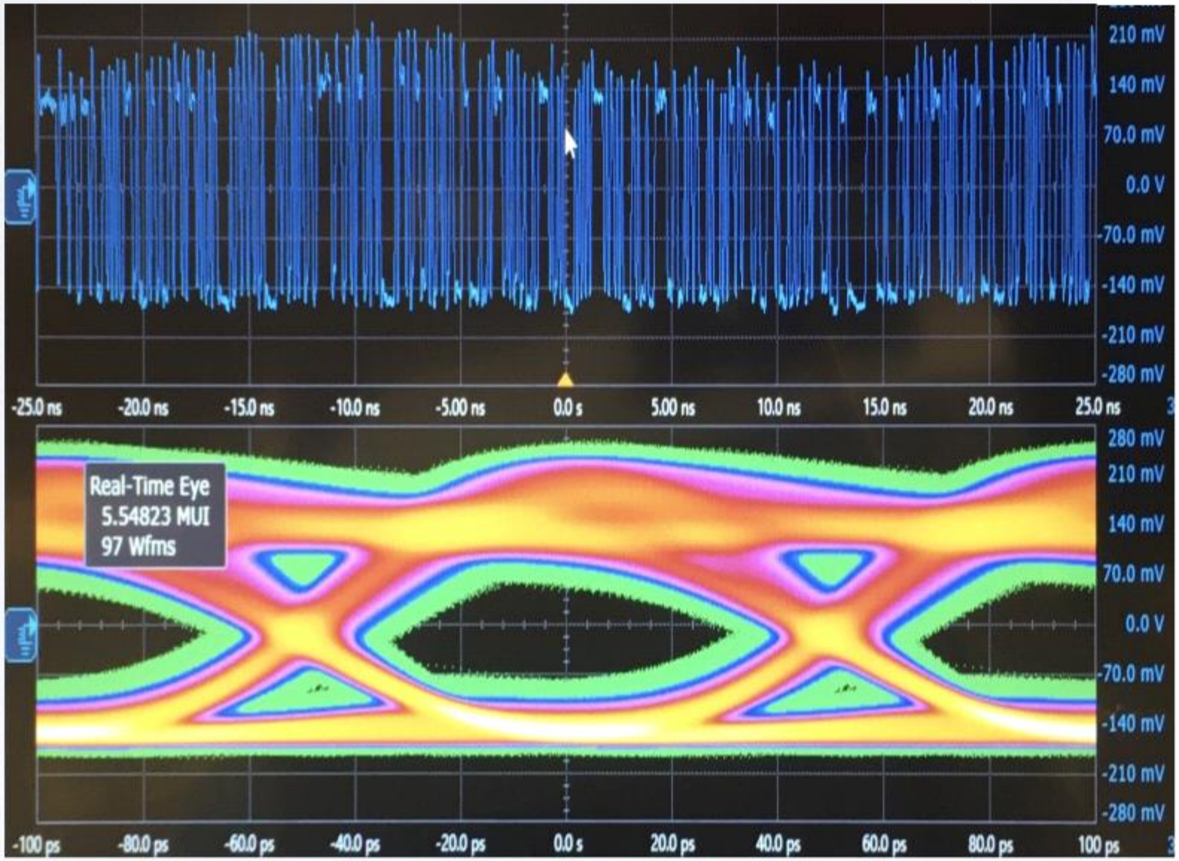
Telecom part



Comb for telecom result



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



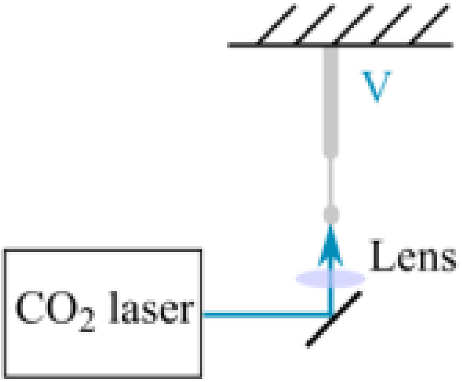
E.A. Anashkina, V. Bobrovs, T. Salgals, I. Brice, J. Alnis, A.V. Andrianov,
Kerr optical frequency combs with multi-FSR mode spacing in silica microspheres
IEEE Photonics Technology Letters 33, 453-456 (2021).

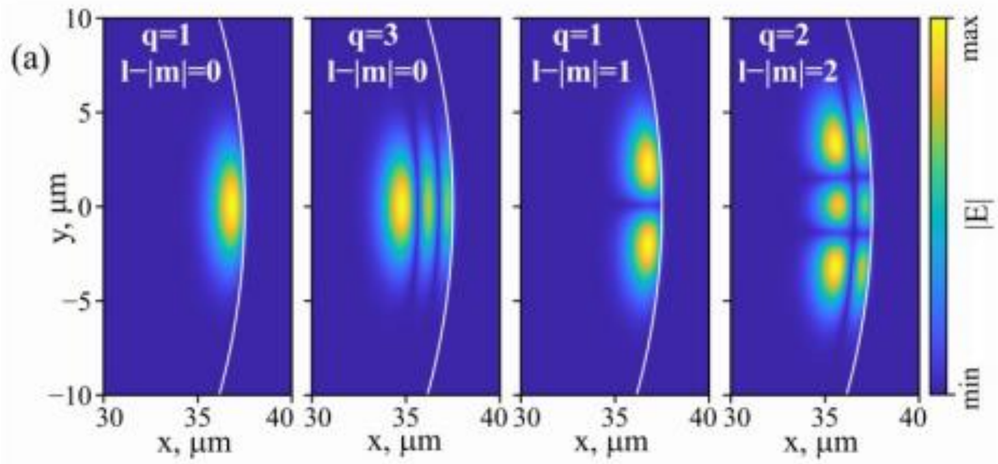
T. Salgals, J. Alnis, R. Murnieks, I. Brice, J. Porins, A. V. Andrianov, E. A. Anashkina, S. Spolitis, V. Bobrovs,
Demonstration of a fiber optical communication system employing a silica microsphere-based OFC source,Optics Express 29, 10903-10913 (2021).

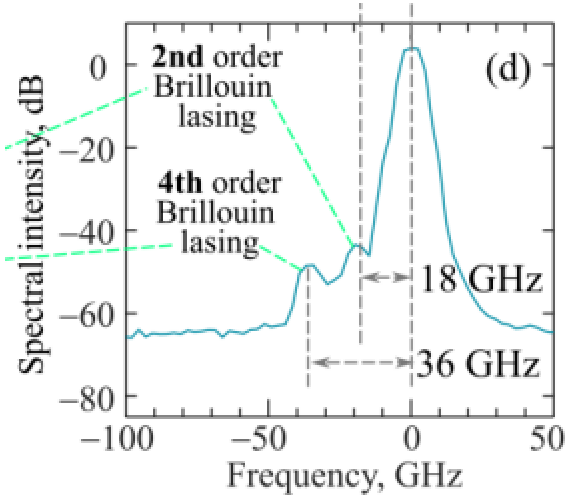
Importance of microsphere roundness: less mode splitting spectral lines

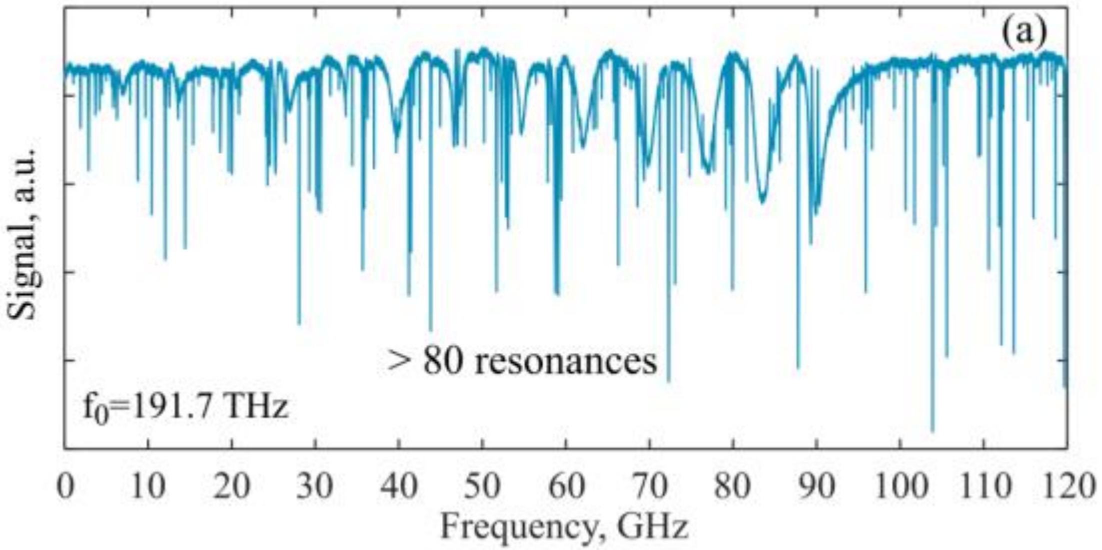
Cascade Brillouin Lasing in a Tellurite-Glass Microsphere Resonator with Whispering Gallery Modes *sensors*

Elena A. Anashkina [1,*], Maria P. Marisova [1], Vitaly V. Dorofeev [1,2] and Alexey V. Andrianov [1]

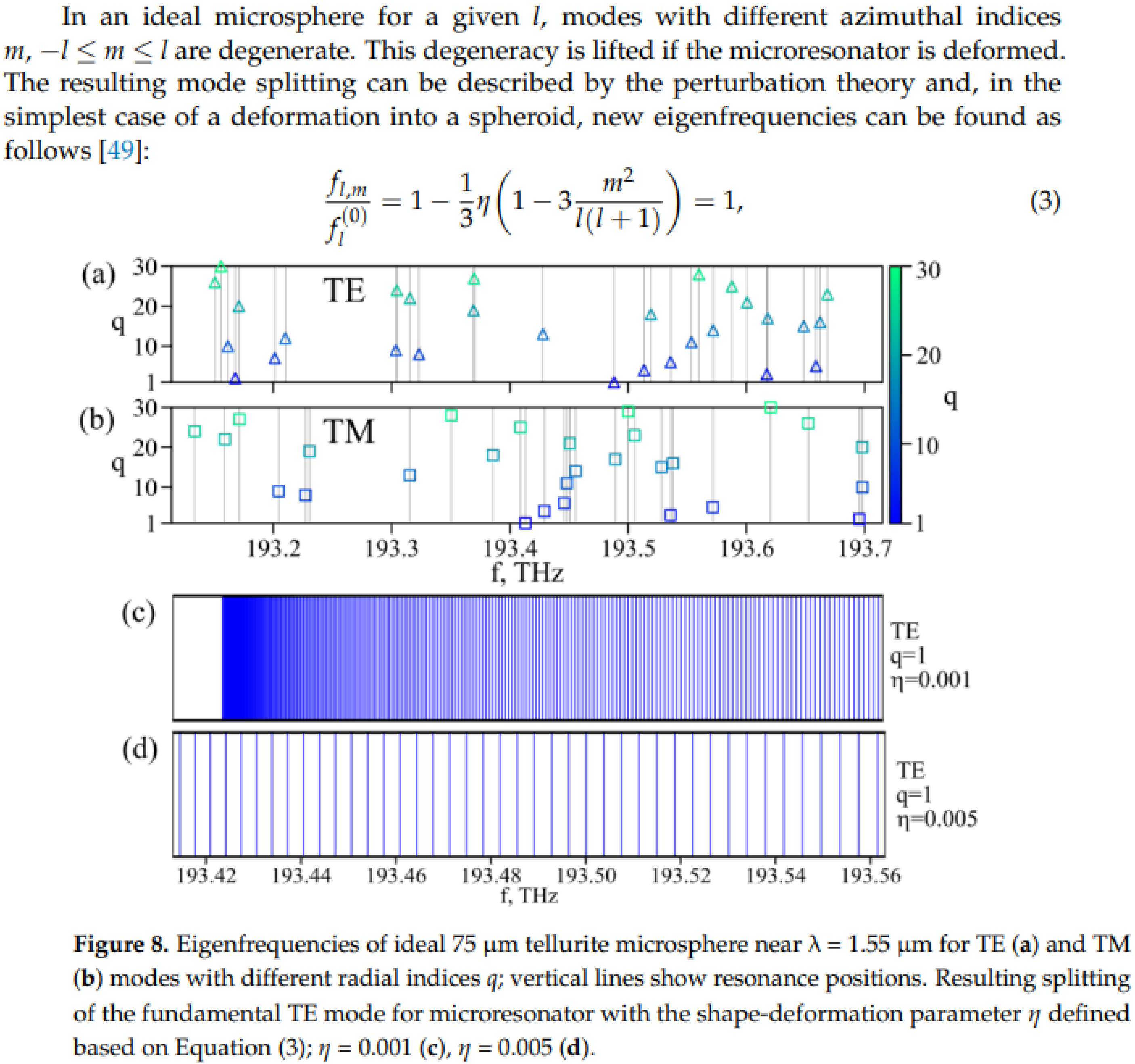








Importance of microsphere roundness: less mode splitting spectral lines



In an ideal microsphere for a given l, modes with different azimuthal indices m, $-l \leq m \leq l$ are degenerate. This degeneracy is lifted if the microresonator is deformed. The resulting mode splitting can be described by the perturbation theory and, in the simplest case of a deformation into a spheroid, new eigenfrequencies can be found as follows [49]:

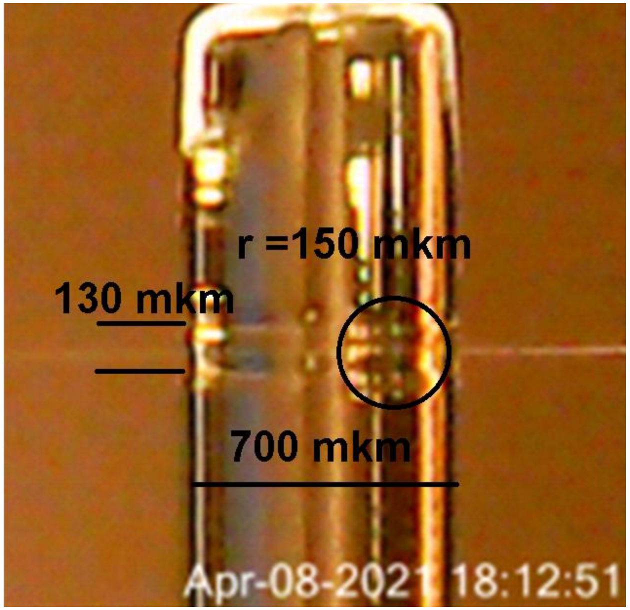
$$\frac{f_{l,m}}{f_l^{(0)}} = 1 - \frac{1}{3}\eta\left(1 - 3\frac{m^2}{l(l+1)}\right) = 1, \tag{3}$$

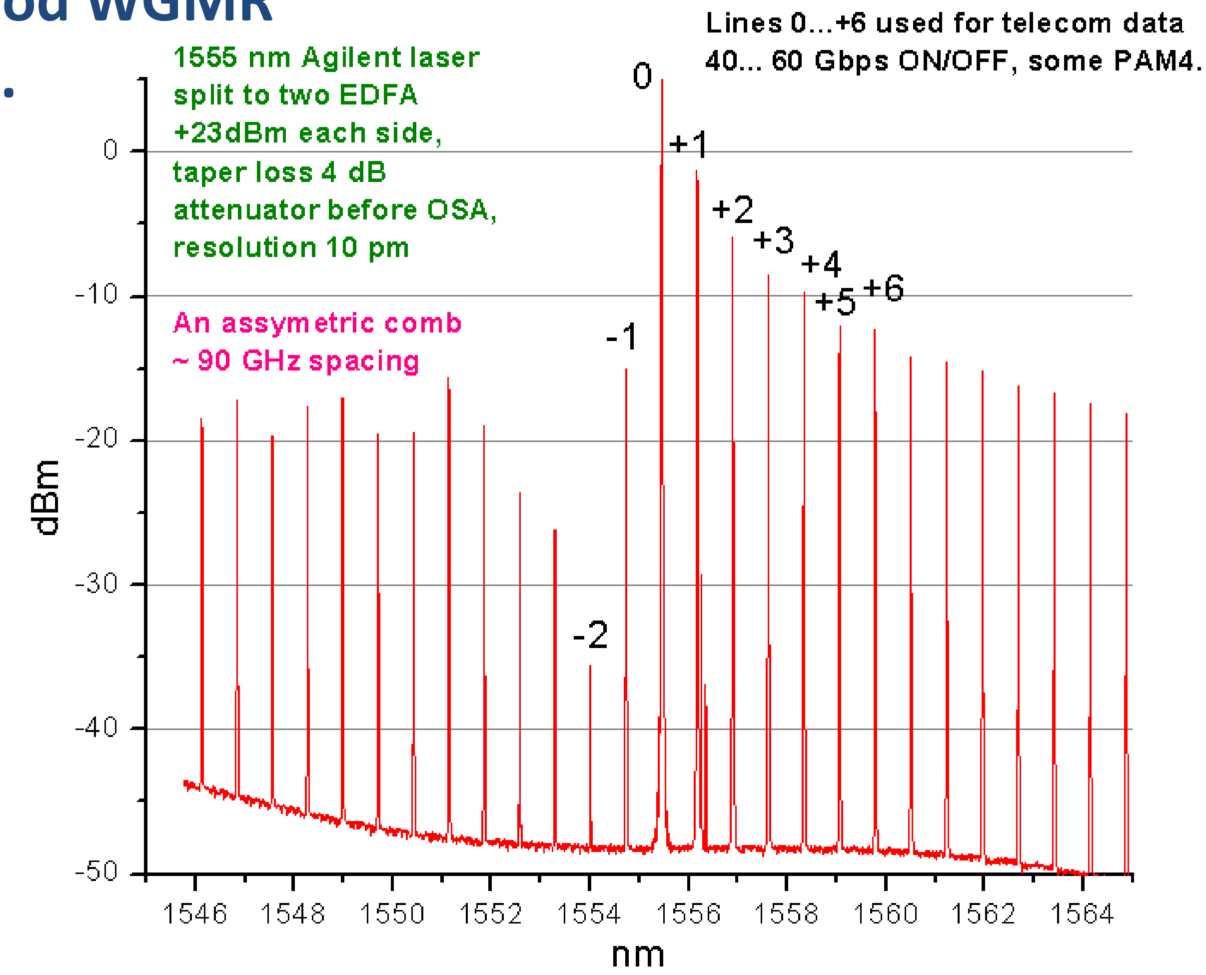
Figure 8. Eigenfrequencies of ideal 75 μm tellurite microsphere near λ = 1.55 μm for TE (**a**) and TM (**b**) modes with different radial indices q; vertical lines show resonance positions. Resulting splitting of the fundamental TE mode for microresonator with the shape-deformation parameter η defined based on Equation (3); $\eta = 0.001$ (**c**), $\eta = 0.005$ (**d**).

T1.3 and T2.1. SiO_2 microrod WGMR made on a CO_2 laser lathe.

FSR optimised to 100 GHz.

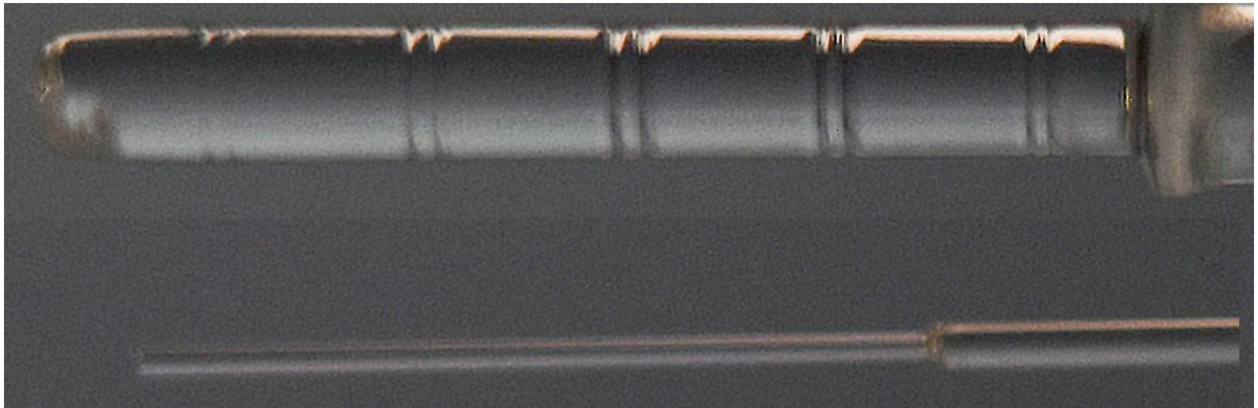
Narrow rim limits the number of spatial modes.




Lines 0...+6 used for telecom data 40... 60 Gbps ON/OFF, some PAM4.

1555 nm Agilent laser split to two EDFA +23dBm each side, taper loss 4 dB attenuator before OSA, resolution 10 pm

An assymetric comb ~ 90 GHz spacing



Conclusions and outlook

Demonstration of World Record: 319 Tb/s Transmission over 3,001 km with 4-core optical fiber

- >120 nm signal bandwidth comprising 552 WDM channels and using both-doped fiber and Raman amplification -

July 12, 2021 Japanese version

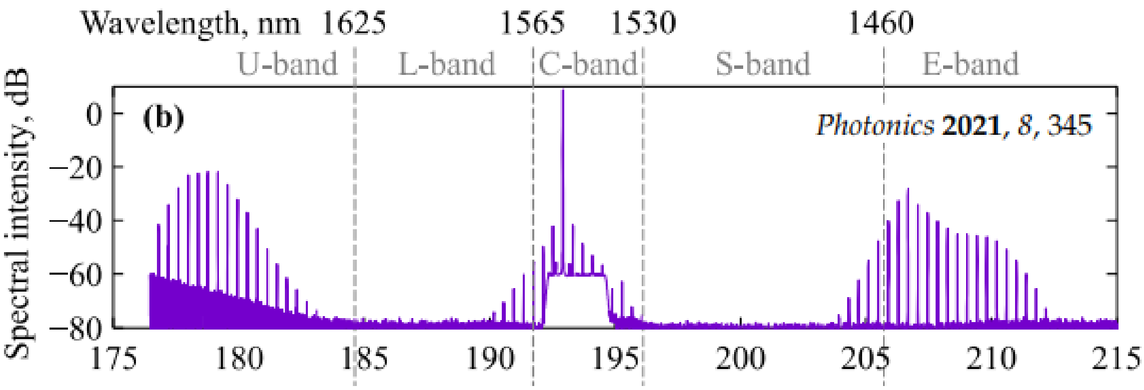
National Institute of Information and Communications Technology

Comb advantages:

- Comb generated channel spacing is well defined and stable..
- In 2021 Japan demonstrated 300 TB/s telecom data transfer using 500 comb lines that would not be possible using 500 individual DFB lasers.

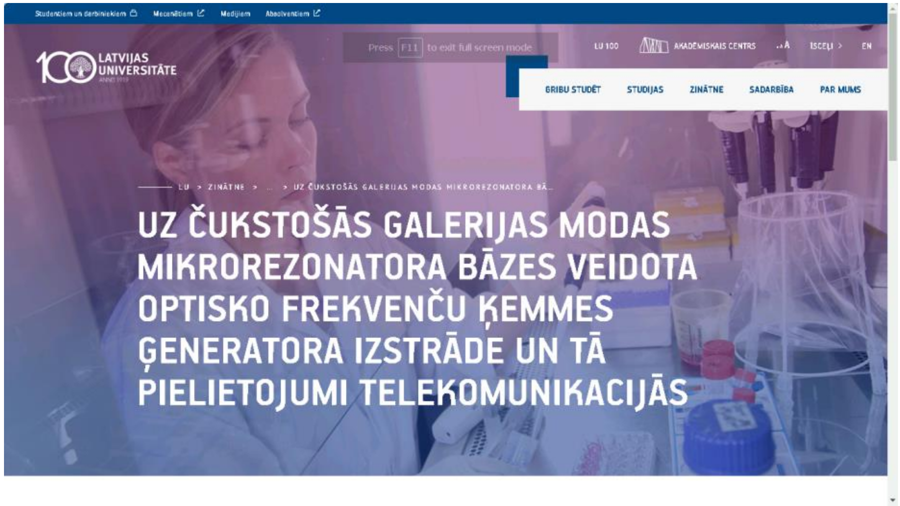
Comb disadvantages:

- Turing roll combs experience some amplitude instability. More stable soliton regime combs we could not get in microspheres do to dominating thermal effects.
- One needs to separate by filter individual comb lines before sending to data modulator.
- Comb lines have exponentially decreasing amplitude away from the pump. We could use only the few strongest lines. Telecom modulators are optimised for channel power of 1 mW (0 dBm).
- Pascal Del‘Haye recommends us to filter out EDFA broadband noise and preamplify and level-out the comb lines with EDFA to telecom levels.

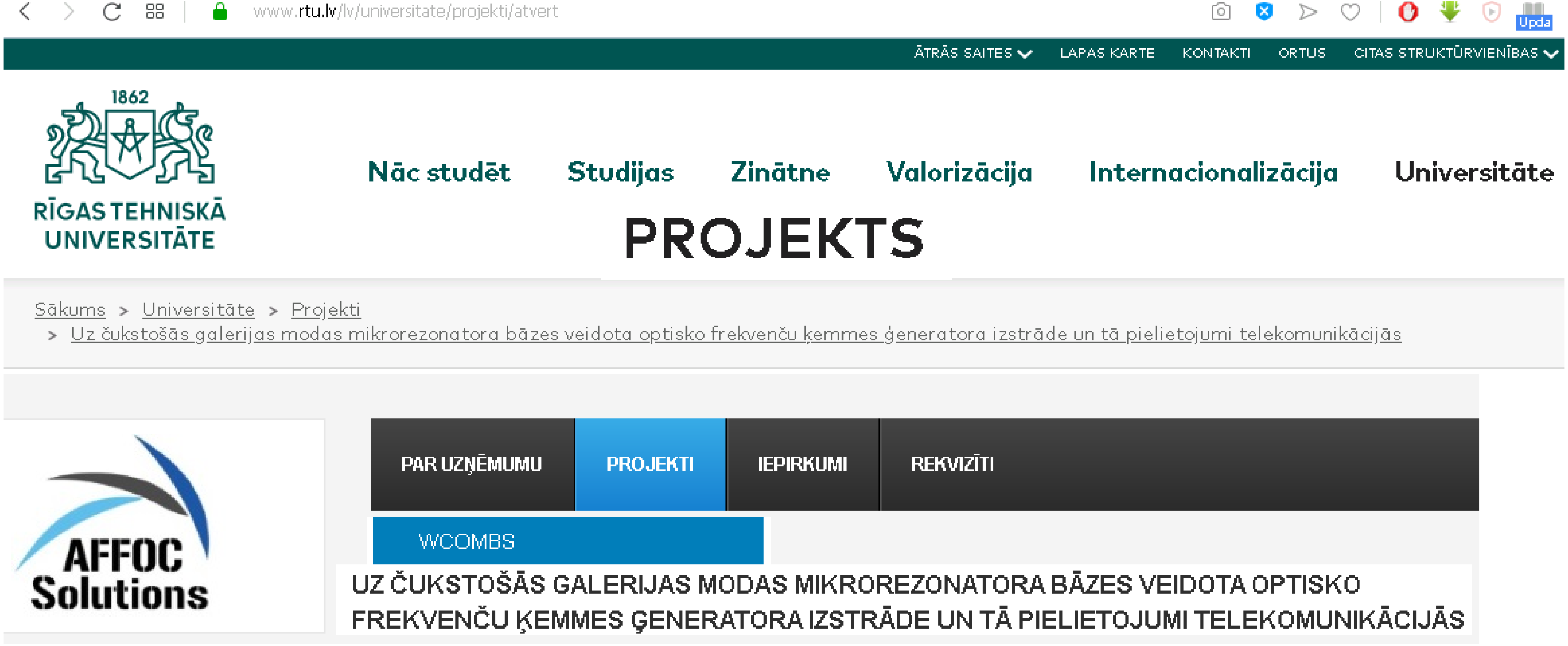


Photonics **2021**, *8*, 345

T4.5. WWW pages of the Project



UZ ČUKSTOŠĀS GALERIJAS MODAS MIKROREZONATORA BĀZES VEIDOTA OPTISKO FREKVENČU ĶEMMES ĢENERATORA IZSTRĀDE UN TĀ PIELIETOJUMI TELEKOMUNIKACIJĀS



PROJEKTS

Sākums > Universitāte > Projekti > Uz čukstošās galerijas modas mikrorezonatora bāzes veidota optisko frekvenču ķemmes ģeneratora izstrāde un tā pielietojumi telekomunikācijās

UZ ČUKSTOŠĀS GALERIJAS MODAS MIKROREZONATORA BĀZES VEIDOTA OPTISKO FREKVENČU ĶEMMES ĢENERATORA IZSTRĀDE UN TĀ PIELIETOJUMI TELEKOMUNIKĀCIJĀS