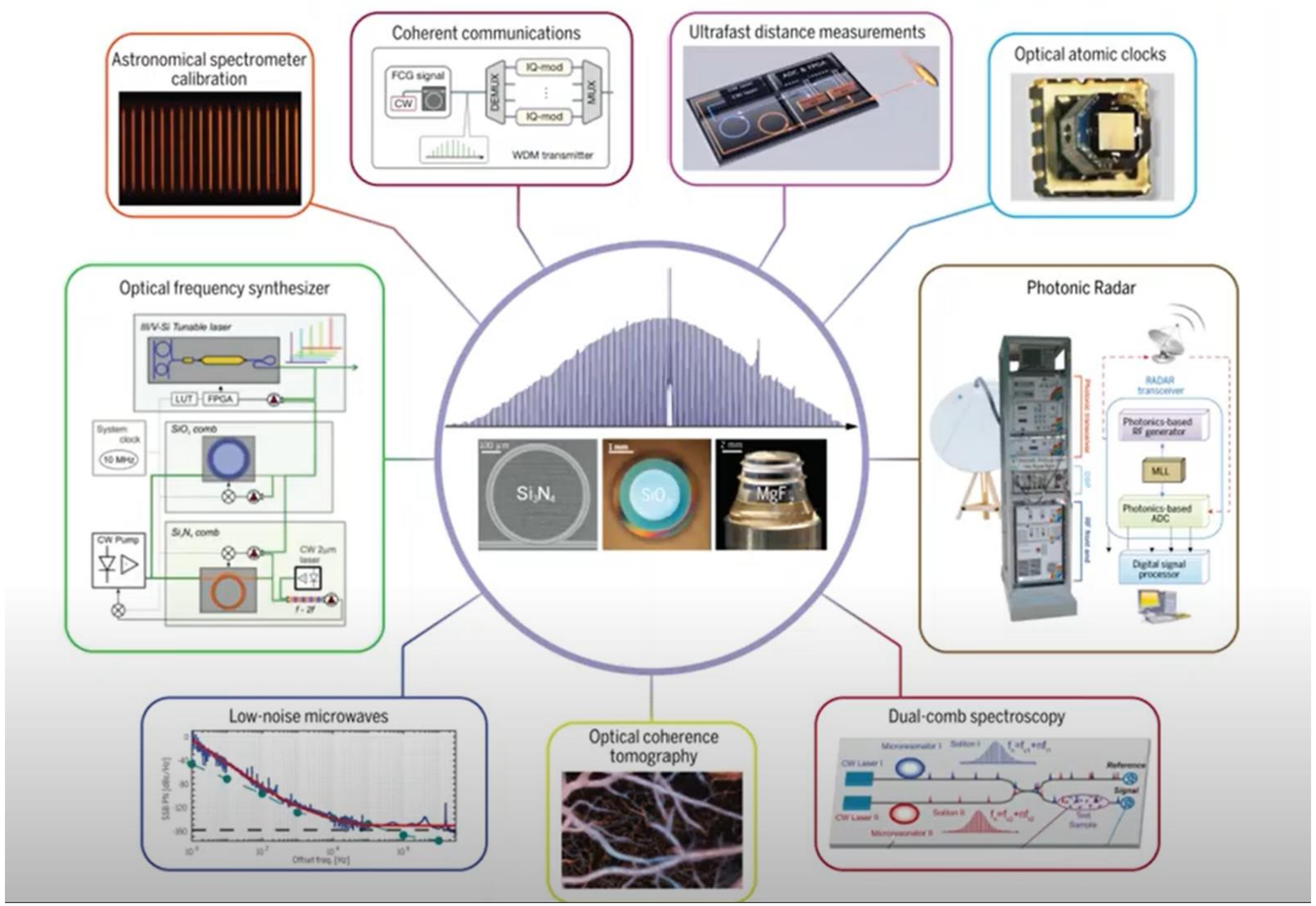
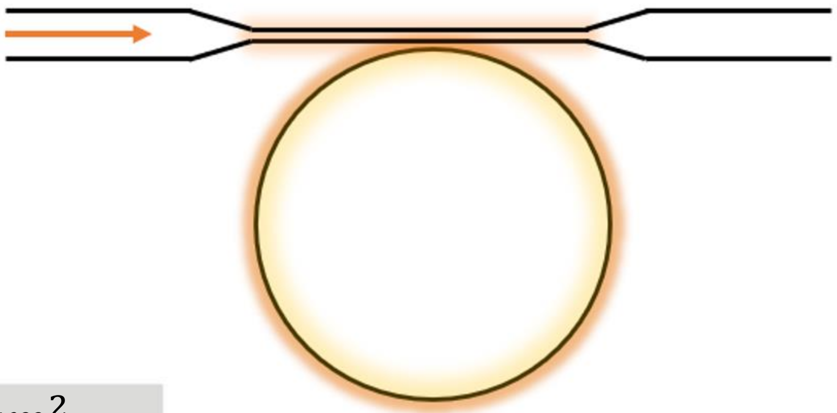
Geometry optimization and soliton comb formation inside whispering gallery mode resonators

Draguns Kristians, Atvars Aigars, Veilande Rita, Alnis Janis

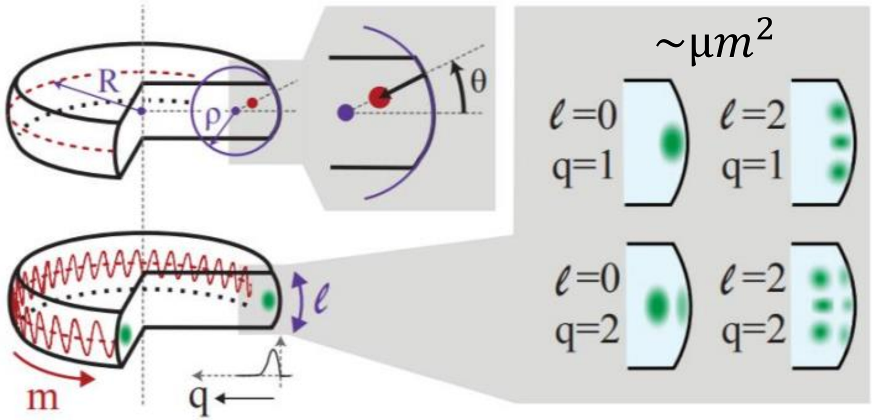
Frequency comb applications

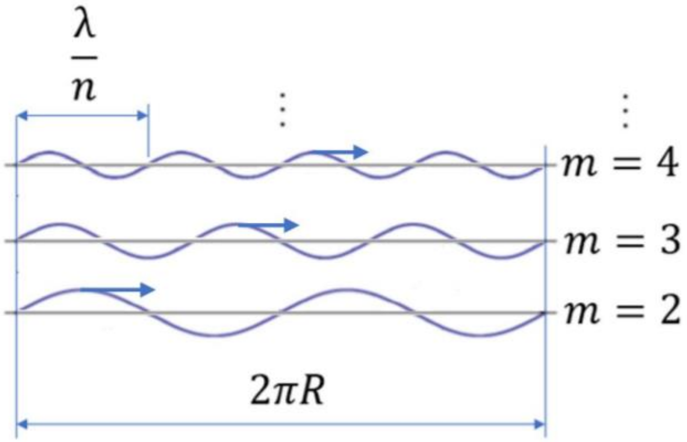


Whispering gallery mode resonators (microresonators)



$$2\pi R = m\frac{\lambda}{n}$$



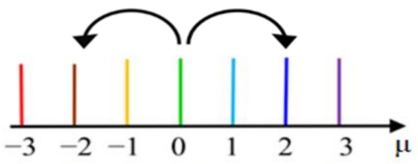


[Schunk, G. , Furst, J. U., Fortsch, M., Strekalov, D. V., Vogl, U., Sedlmeir, F., Schwefel, H. G. L., Leuchs, G., Marquardt, C., Identifying modes of large whispering-gallery mode resonators from the spectrum and emission pattern, Opt. Express 22(25), 30795–30806 (2014)]

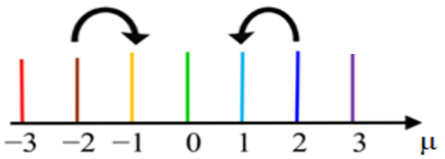
High intensity → nonlinear effects

$$Intensity = \frac{Power}{Area}\left[\frac{W}{m^2}\right]$$

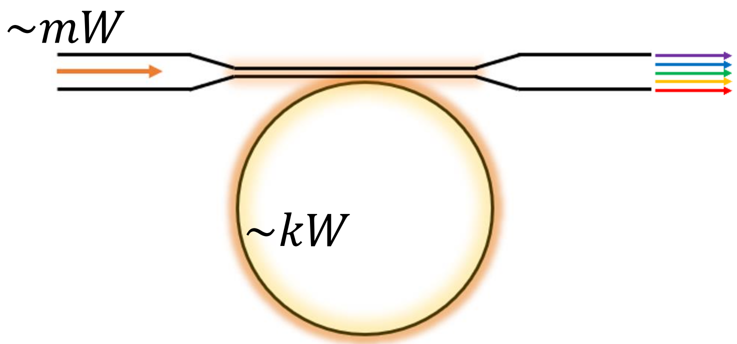
Four-wave mixing:



$$2\hbar\omega_0 \rightarrow \hbar\omega_{-2} + \hbar\omega_2$$

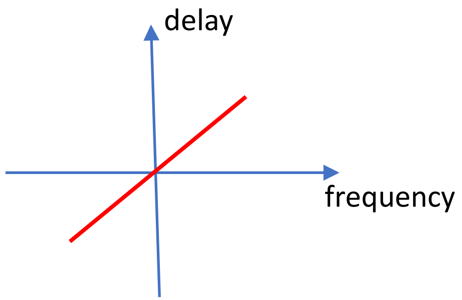


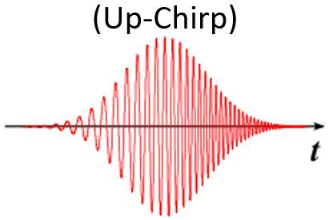
$$\hbar\omega_{-2} + \hbar\omega_2 \rightarrow \hbar\omega_{-1} + \hbar\omega_1$$



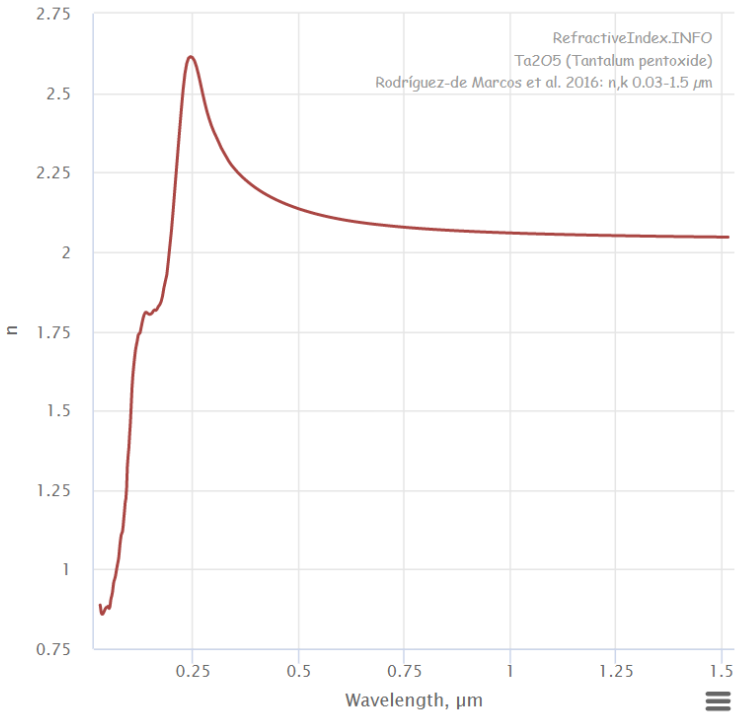
$$Kerr\ effect: \quad n = n_0 + n_2 I$$

$$n_2(Ta_2O_5, 1550nm) = 10^{-14}\left[\frac{cm^2}{W}\right]$$

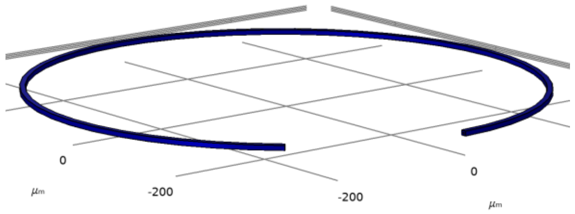




Dispersion

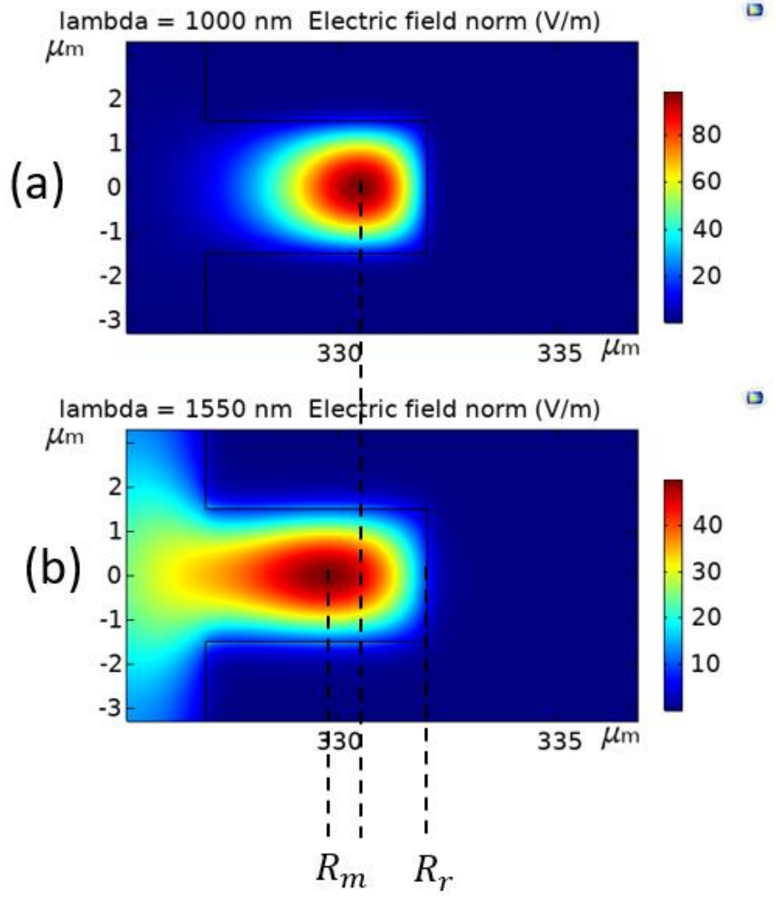


Material dispersion



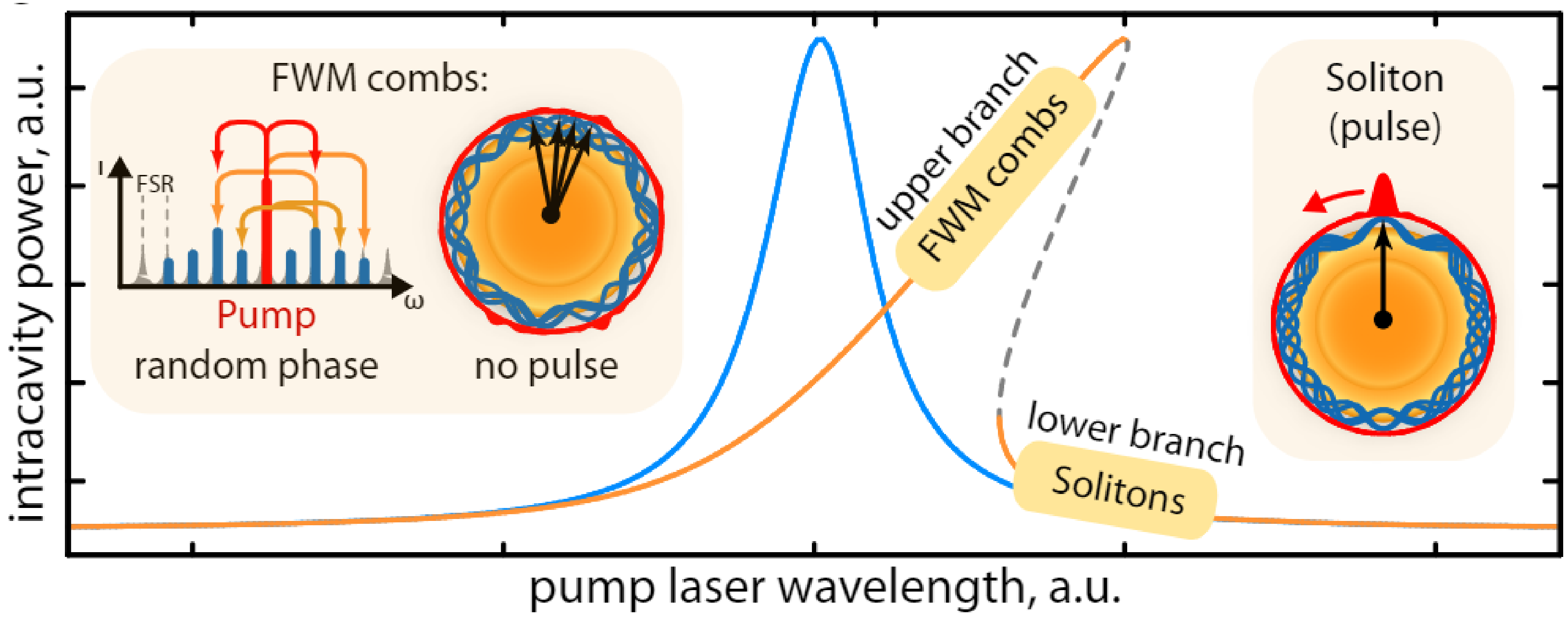
$$2\pi \color{red}{R} = m\frac{\lambda}{\color{red}{n}}$$

Geometric dispersion



[https://refractiveindex.info/?shelf=main&book=Ta2O5&page=Rodriguez-de_Marcos]

Non-lorentzian resonance shape

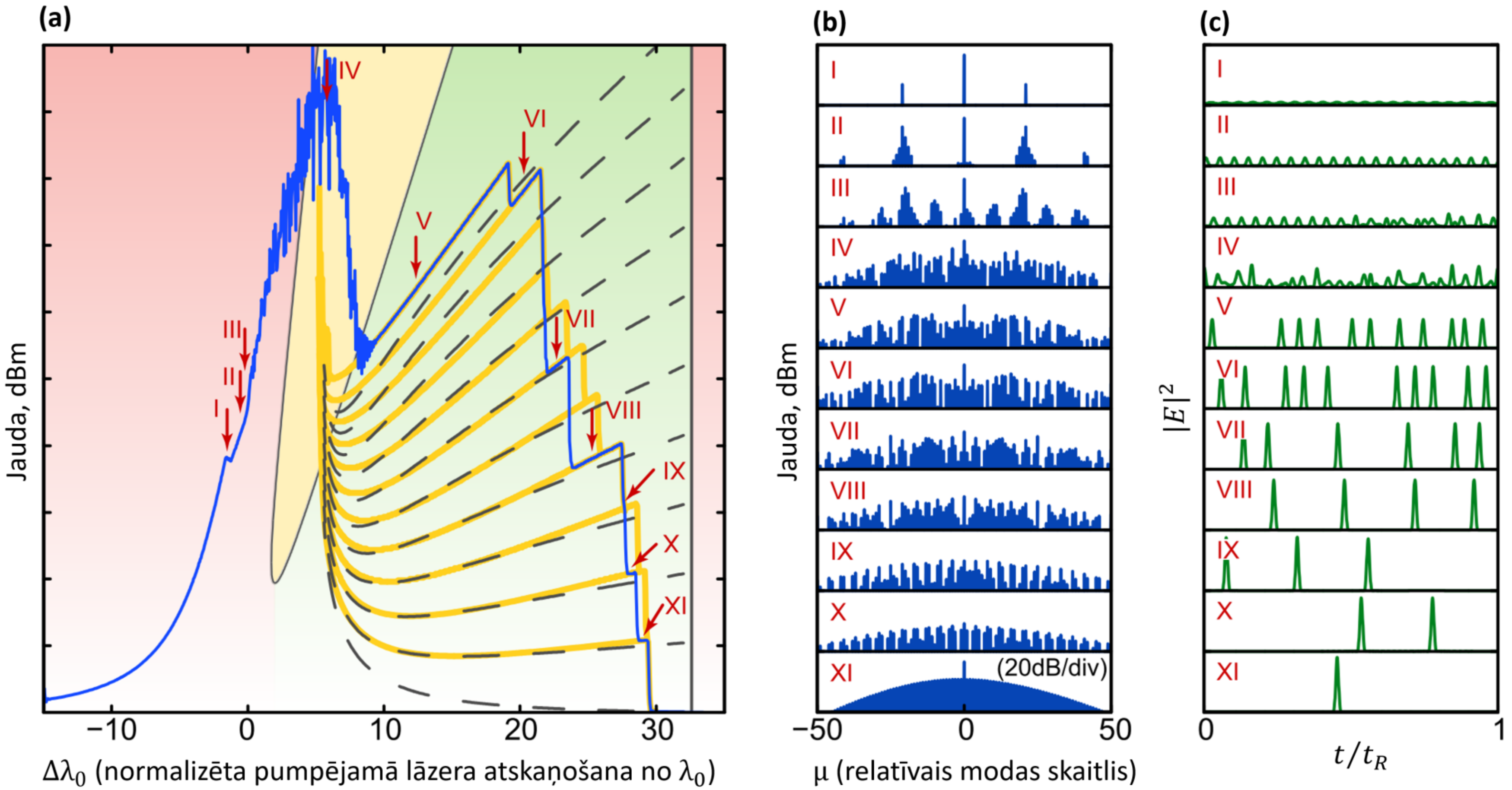


$$2\pi R = m\frac{\lambda}{n}$$

$$n = n_0 + n_2 I$$

[Herr, T., Brasch, V., Jost, J. D., Wang, C. Y., Kondratiev, N. M., Gorodetsky, M. L., & Kippenberg, T. J. (2014). Temporal solitons in optical microresonators. *Nature Photonics*, *8*(2), 145–152. https://doi.org/10.1038/nphoton.2013.343]

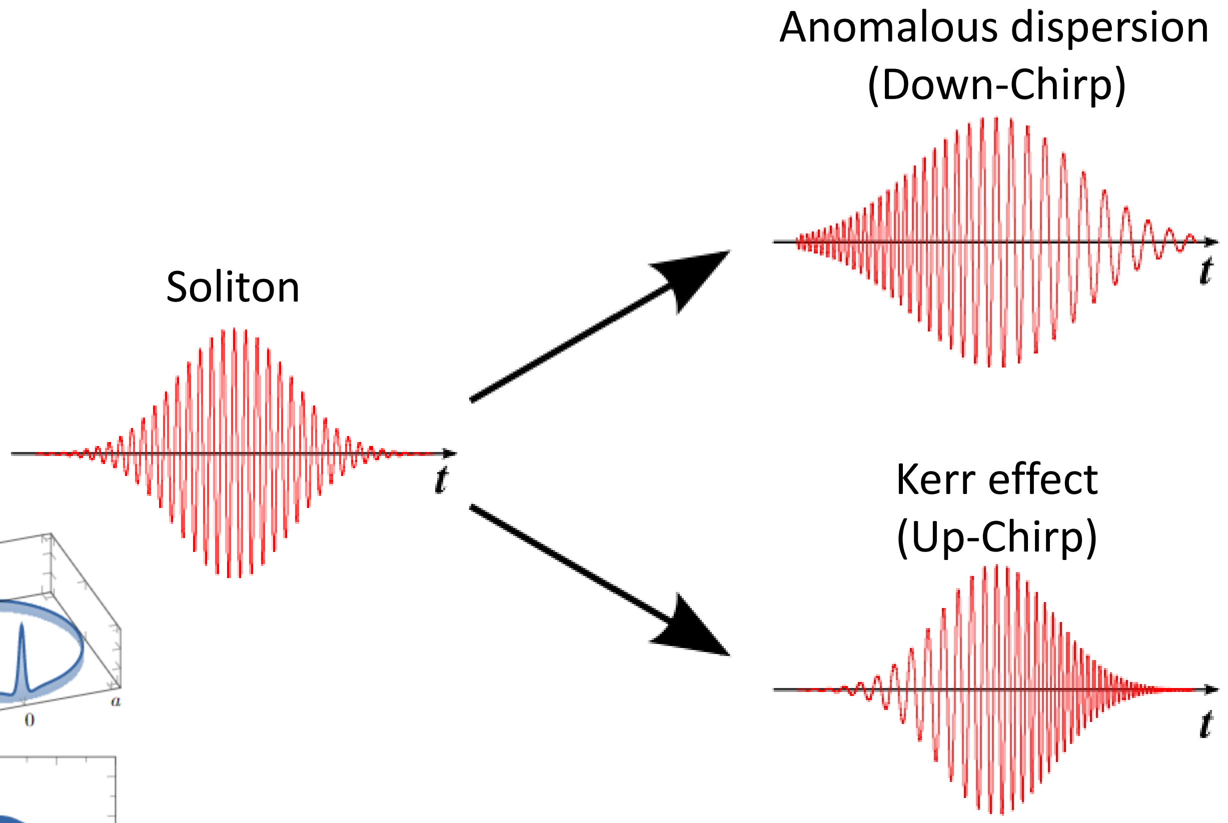
Detuning

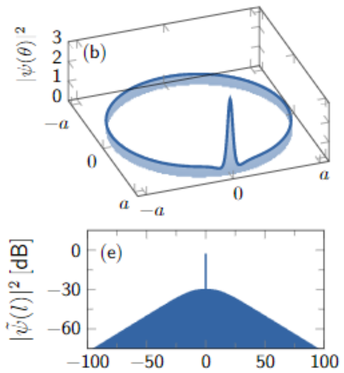


[Herr, T., Brasch, V., Jost, J. D., Wang, C. Y., Kondratiev, N. M., Gorodetsky, M. L., & Kippenberg, T. J. (2014). Temporal solitons in optical microresonators. *Nature Photonics*, *8*(2), 145–152. https://doi.org/10.1038/nphoton.2013.343]

Soliton formation

A soliton is a self-reinforcing wave packet that maintains its shape while it propagates at a constant velocity. Solitons are caused by a cancellation of nonlinear and dispersive effects in the medium.





Chembo, Y. K. (2016). Kerr optical frequency combs: Theory, applications and perspectives. *Nanophotonics*, *5*(2), 214–230. https://doi.org/10.1515/nanoph-2016-0013

Lugiato-Lefever equation

$$t_R \frac{\partial E(t,\tau)}{\partial t} = -\left(\frac{\alpha}{2} - i\delta_0\right)E + i \cdot FT^{-1}\left[-t_R D_{int}(\omega) \cdot FT[E(t,\tau)]\right] + \gamma |E|^2 E + \sqrt{\theta} E_{in}$$

Round trip

Loss coeficient

Detuning

Integrated dispersion

Nonlinearity coeficient

Coupling coefficient

$$\gamma = \frac{2\pi}{\lambda}\frac{n_2}{A_{eff}}\left[\frac{rad}{W \cdot m}\right]$$

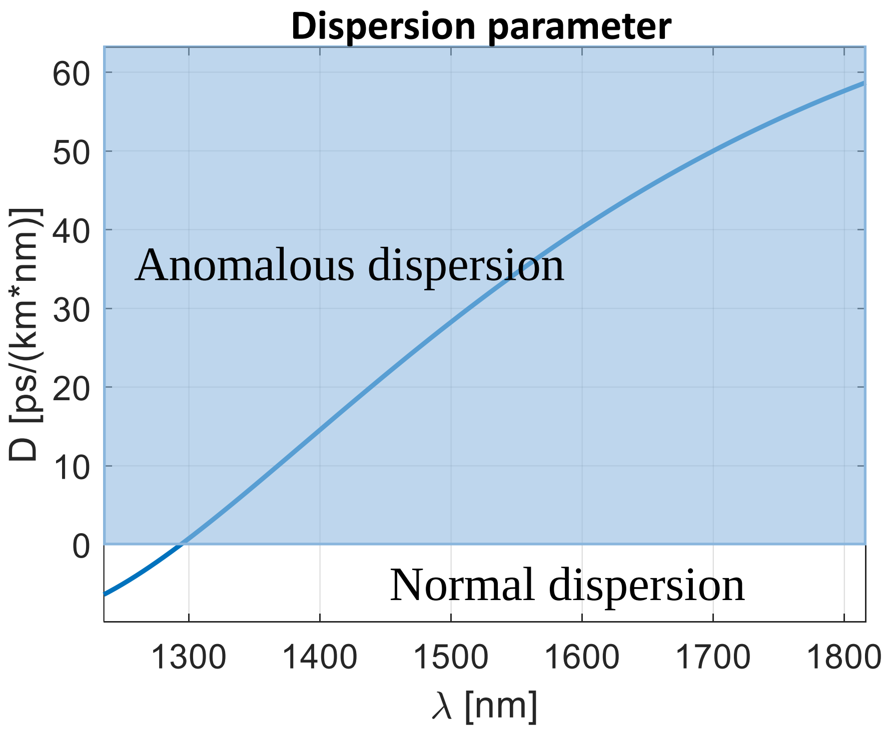
$$A_{eff} = \frac{\left(\int |E|^2 dS\right)^2}{\int |E|^4 dS}\ [\mu m^2]$$

$$f_\mu = f_0 + D_1\mu + \frac{1}{2}D_2\mu^2 + \frac{1}{6}D_3\mu^3 + \frac{1}{24}D_4\mu^4 + \cdots = f_0 + D_1\mu + D_{int}$$

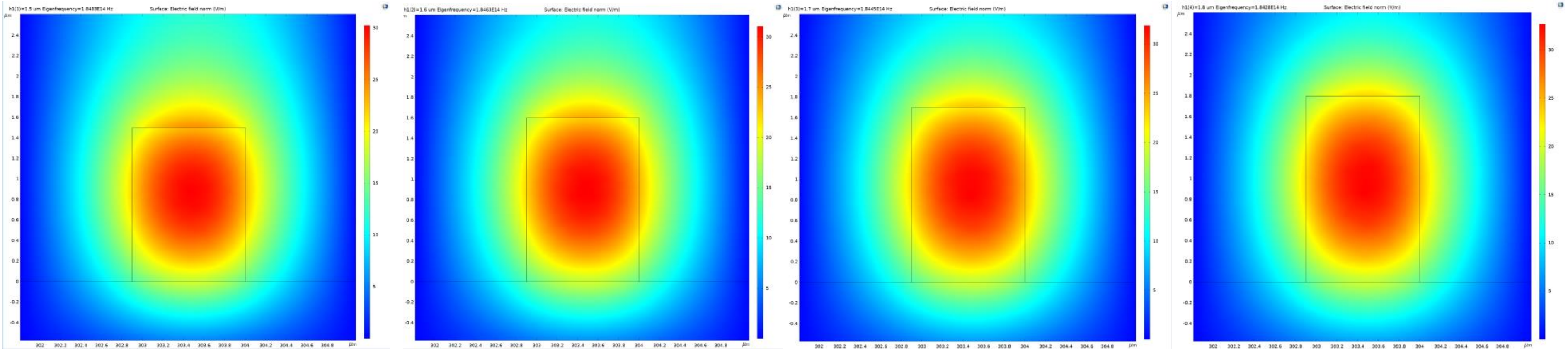
FEM solver COMSOL

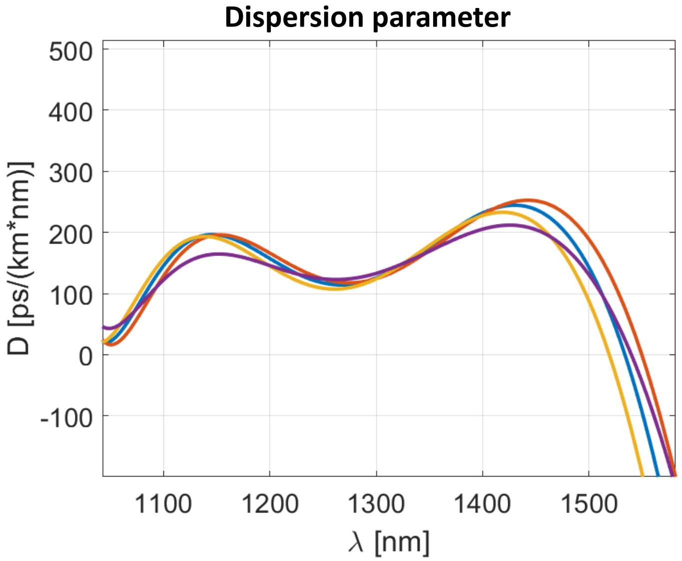
$$D = -\frac{2\pi c}{\lambda^2}\frac{\partial^2 k}{\partial \omega^2}\left[\frac{ps}{nm\ km}\right]$$

$$k = \frac{2\pi n}{\lambda} = \frac{m}{R}$$



m	λ, µm	Frequency, Hz	neff	reff, m	Aeff, µm^2
1600	1.613964	185749204925205	1.406245	0.00029226237019	3.33276793
1601	1.613099	185848744960256	1.406372	0.00029226207363	3.33146485
1602	1.612236	185948290218364	1.406498	0.00029226177662	3.33016082
1603	1.611373	186047840685406	1.406624	0.00029226147916	3.32885584
1604	1.610511	186147396350256	1.406751	0.00029226118125	3.32754990
1605	1.60965	186246957197855	1.406877	0.00029226088288	3.32624297
1606	1.60879	186346523216125	1.407002	0.00029226058406	3.32493507
1607	1.607931	186446094392028	1.407128	0.00029226028479	3.32362616
…	…	…	…	…	…


h1(1)=1.5 um Eigenfrequency=1.8483E14 Hz
Surface: Electric field norm (V/m)
h1(2)=1.6 um Eigenfrequency=1.8463E14 Hz
Surface: Electric field norm (V/m)
h1(3)=1.7 um Eigenfrequency=1.8445E14 Hz
Surface: Electric field norm (V/m)
h1(4)=1.8 um Eigenfrequency=1.8428E14 Hz
Surface: Electric field norm (V/m)

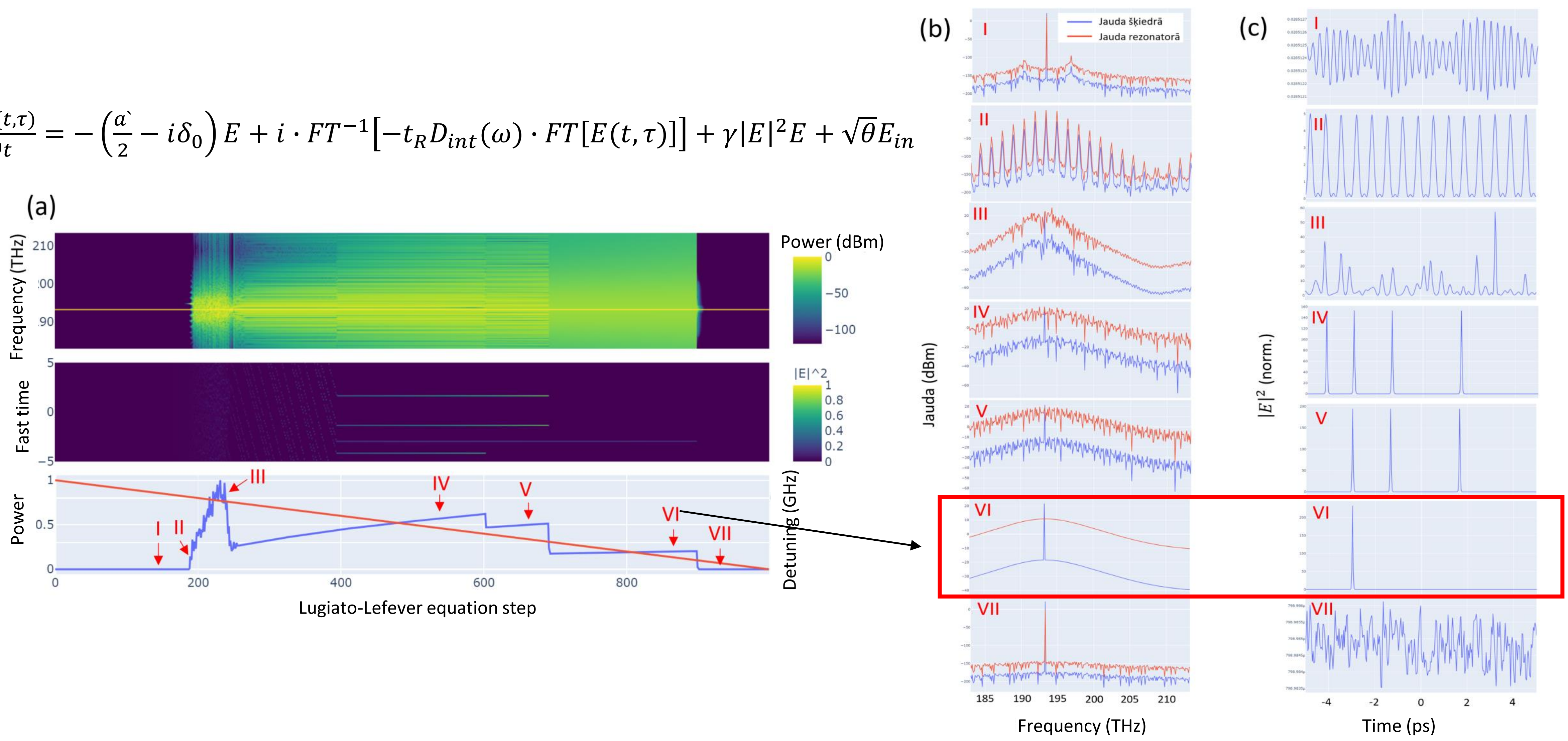

Dispersion parameter
D [ps/(km*nm)]
500
400
300
200
100
0
-100
1100
1200
1300
1400
1500
λ [nm]

Ta_2O_5 resonator geometry optimisation process

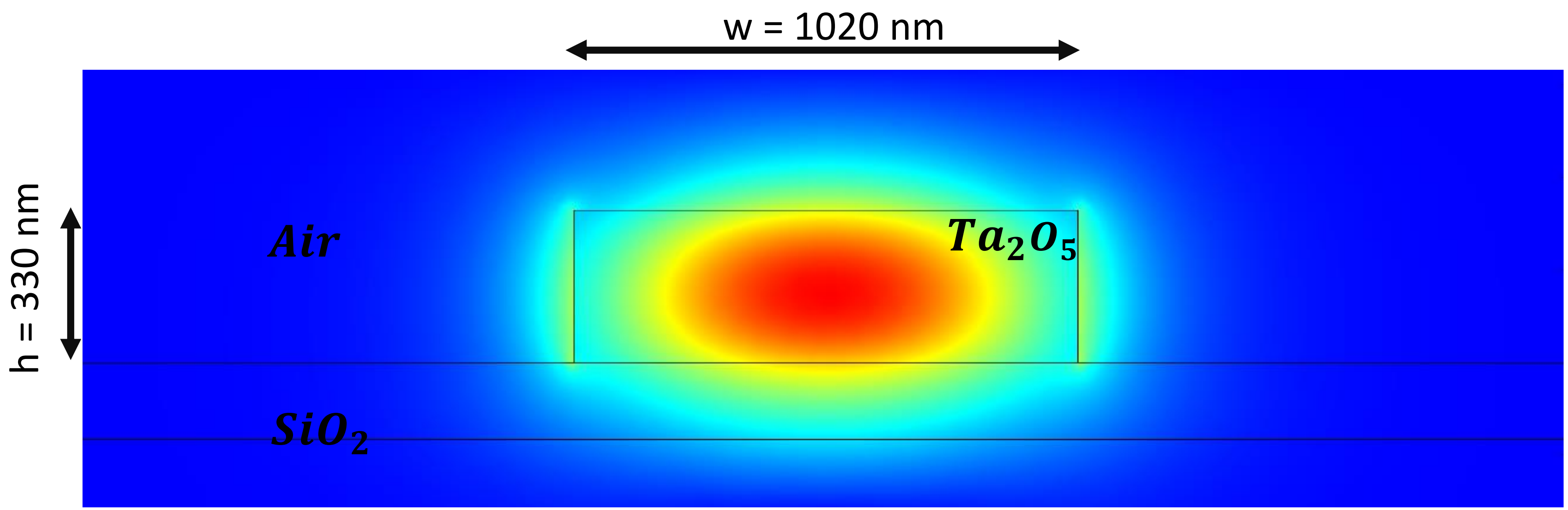
- 1) Initial geometry
- 2) Parametric sweep m
- 3) Calculate dispersion
- 4) Change geometry, repeat

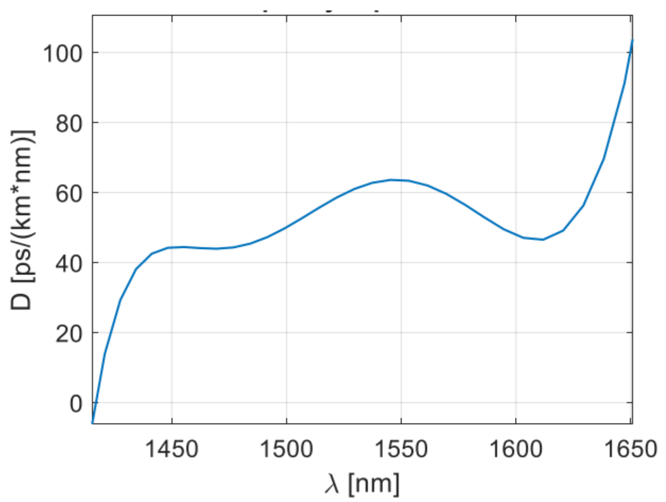
python pyLLE

$$t_R \frac{\partial E(t,\tau)}{\partial t} = -\left(\frac{\alpha}{2} - i\delta_0\right)E + i\cdot FT^{-1}\left[-t_R D_{int}(\omega)\cdot FT[E(t,\tau)]\right] + \gamma|E|^2 E + \sqrt{\theta}E_{in}$$



End result


w = 1020 nm
h = 330 nm
Air
Ta_2O_5
SiO_2


100
80
60
40
20
0
D [ps/(km*nm)]
1450
1500
1550
1600
1650
λ [nm]

Thank you for attention!

kristians.draguns@lu.lv

Funding from project ERDF No. 1.1.1.1/18/A/155

NACIONĀLAIS ATTĪSTĪBAS PLĀNS 2020

EIROPAS SAVIENĪBA
Eiropas Reģionālās attīstības fonds

IEGULDĪJUMS TAVĀ NĀKOTNĒ