80. Latvijas Universitātes starptautiskā zinātniskā konference 2022

LATVIJAS UNIVERSITĀTE
ATOMFIZIKAS UN SPEKTROSKOPIJAS INSTITŪTS

Pārskata ziņojums par ERAF projekta Nr. 1.1.1.1/18/A/155 “Uz čukstošās galerijas modas mikrorezonatora bāzes veidota optisko frekvenču ķemmes ģeneratora izstrāde un tā pielietojumi telekomunikacijās” īstenošanu

Report on ERDF project no. 1.1.1.1/18/A/155 “Development of Optical Frequency Comb Generator Based on a Whispering Gallery Mode Microresonator and its Applications in Telecommunications”

I. Brice, A. Sedulis, J. Alnis

NACIONĀLAIS ATTĪSTĪBAS PLĀNS 2020
EIROPAS SAVIENĪBA
Eiropas Reģionālās attīstības fonds
IEGULDĪJUMS TAVĀ NĀKOTNĒ

Par projektu

Projekta partneri:

- Latvijas Universitāte (vadošais partneris, 40% projekta finansējuma)
- Rīgas Tehniskā universitāte, Telekomunikāciju institūts (partneris, 20% finansējuma)
- SIA "AFFOC Solutions" (partneris, 40% finansējuma)

Projekta īstenošanas laiks:

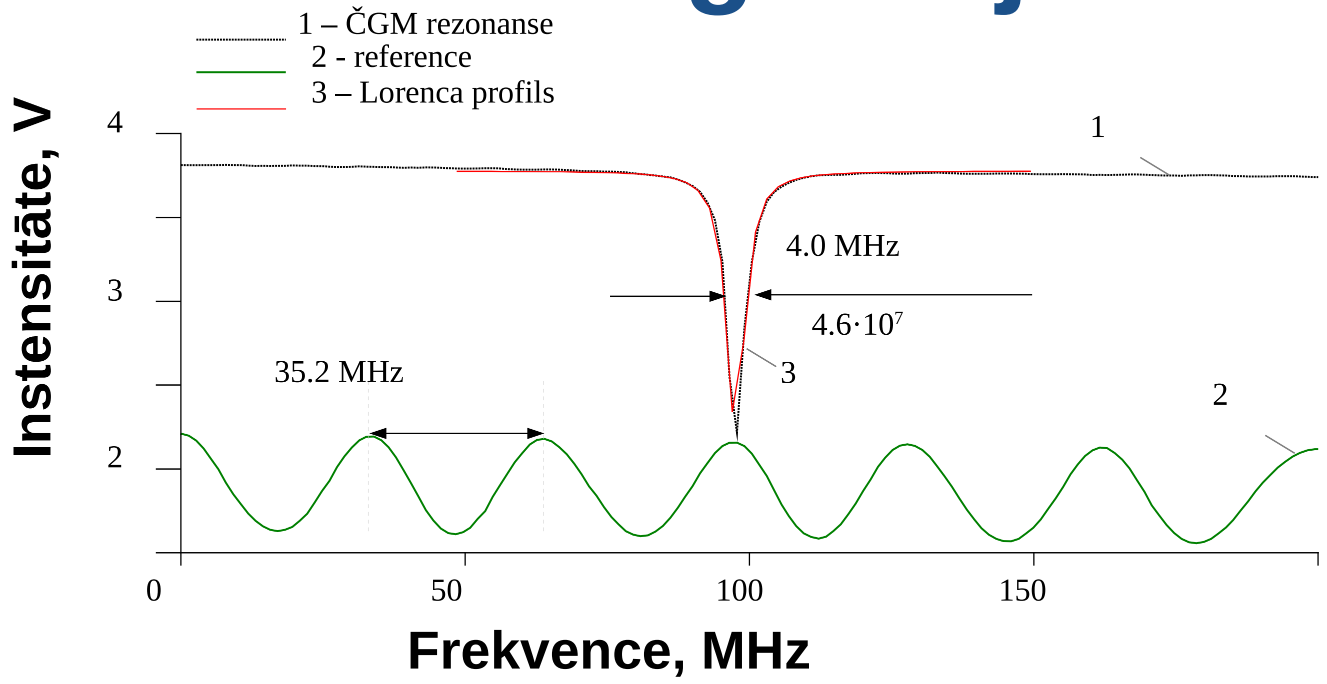
- 36 mēneši, 16.05.2019. - 15.05.2022.

Par projektu

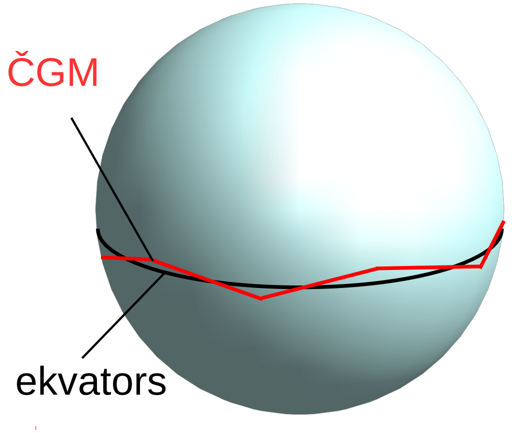
Projekta galvenie sasniedzamie rezultāti:

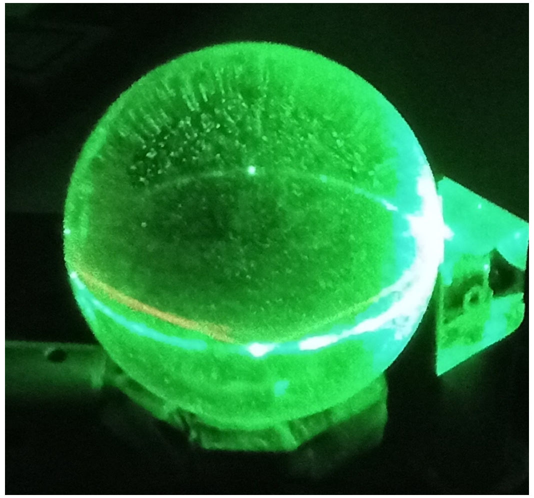
- Zinātniskie raksti – 5; no tiem publicēti augsti citējamos žurnālos vai konferenču rakstu krājumos – 2
- Jauni komercializējami produkti/tehnoloģijas – 1
- Jauni produkti/tehnoloģiju prototipi – 3
- Komersantu, kuri sadarbojas ar pētniecības organizāciju – 1
- Tehnoloģiju tiesības - patents – 1

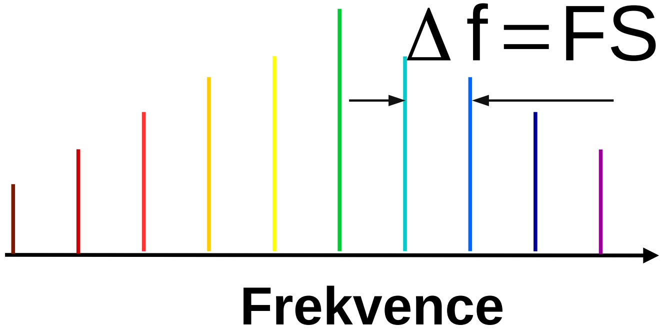
Čukstošās galerijas modu rezonators



$$N\lambda = 2\pi R n$$







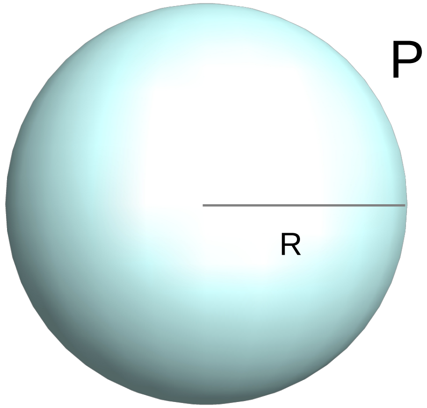
$$\Delta f = \mathrm{FSR} = \frac{c}{2\pi R n}$$

pumpējošā jauda +
augsts labuma foators +
nelināries efekti →
optiskā frekvenču ķemme

Rezonatoru ģeometrija

Mikrosfēra

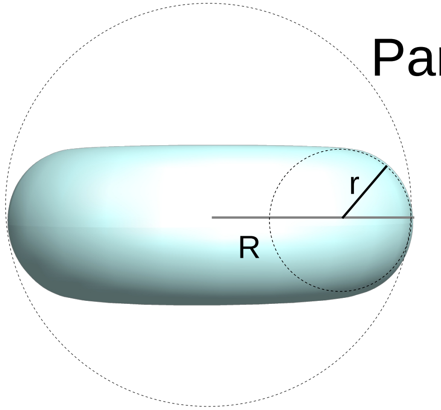
Parametri
R

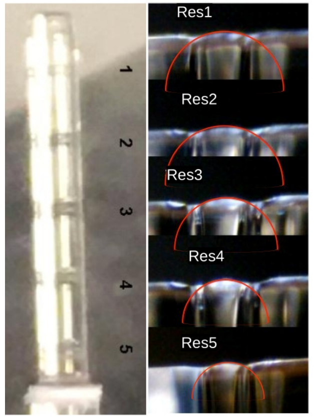


d, µm izmērītaus	f_{FSR}, GHz izērītais	f_{FSR}, GHz izrēķinātais
270 ± 10	288 ± 15	246 ± 9
120 ± 5	538 ± 12	553 ± 23
166 ± 5	397 ± 10	400 ± 12
170 ± 5	392 ± 5	390 ± 11

Mikrotoroīds

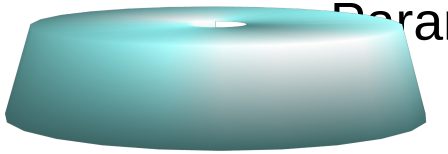
Parametri
R
r



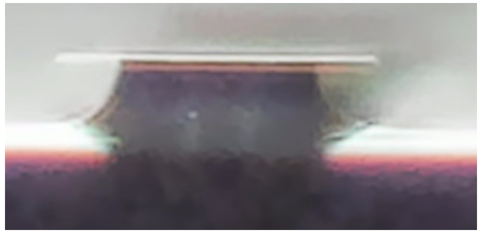


No.	f_{FSR}, GHz izmērītais
1	97.8±0.2
2	99.8±0.2
3	101.0±0.4
4	102.1±0.2
5	103.1±0.2

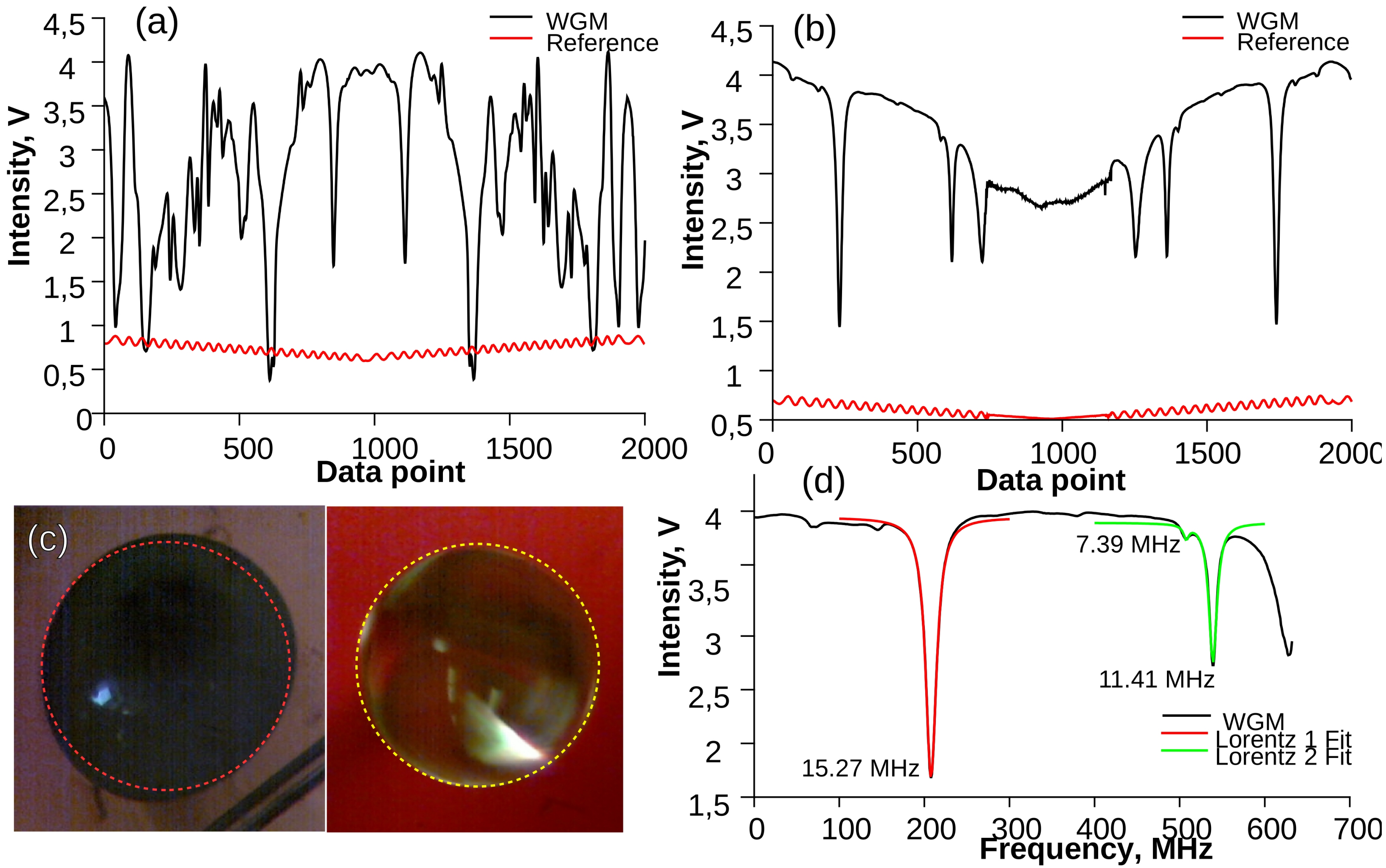
Mikrodisks/ Mikrogredzens



Parametri
R
d
θ



Rezonatoru ģeometrija

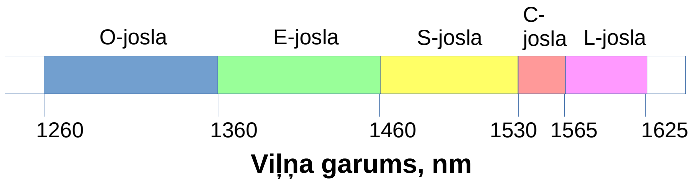


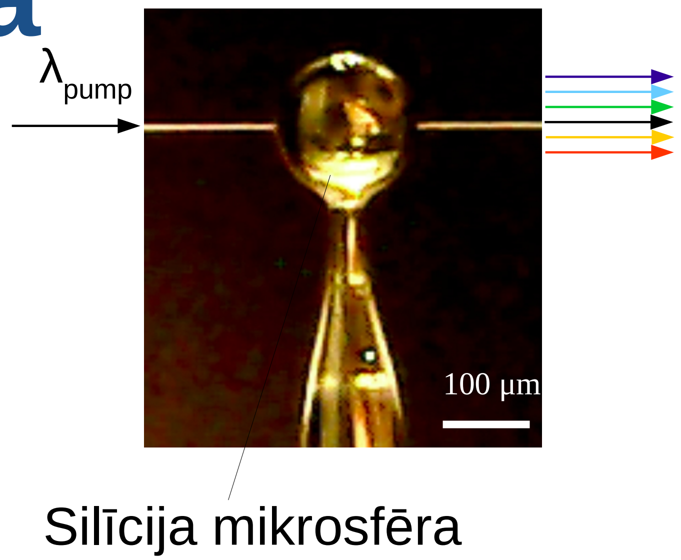
Sfēriska rezonatora ekscentritāte nosaka, cik blīvs ir rezonanšu spektrs

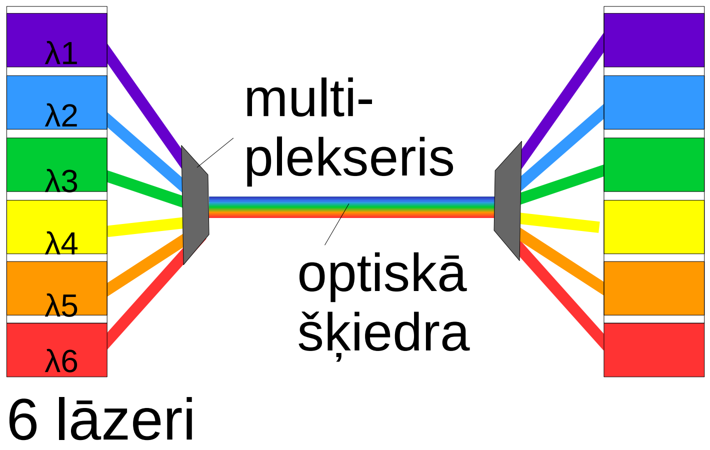
Viļņgarumdales multipleksēšana

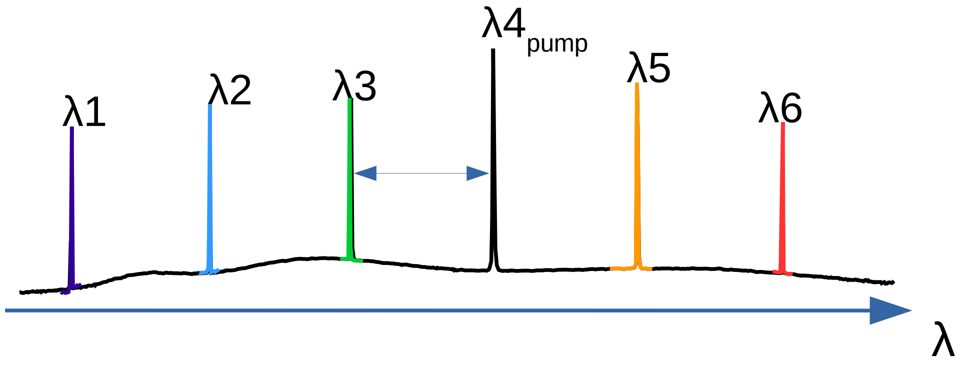
Priekšrocības:

- Aizstāt dārgus lāzera blokus
- Ģenerētās ķemmes līnijas ir ekvidistantas

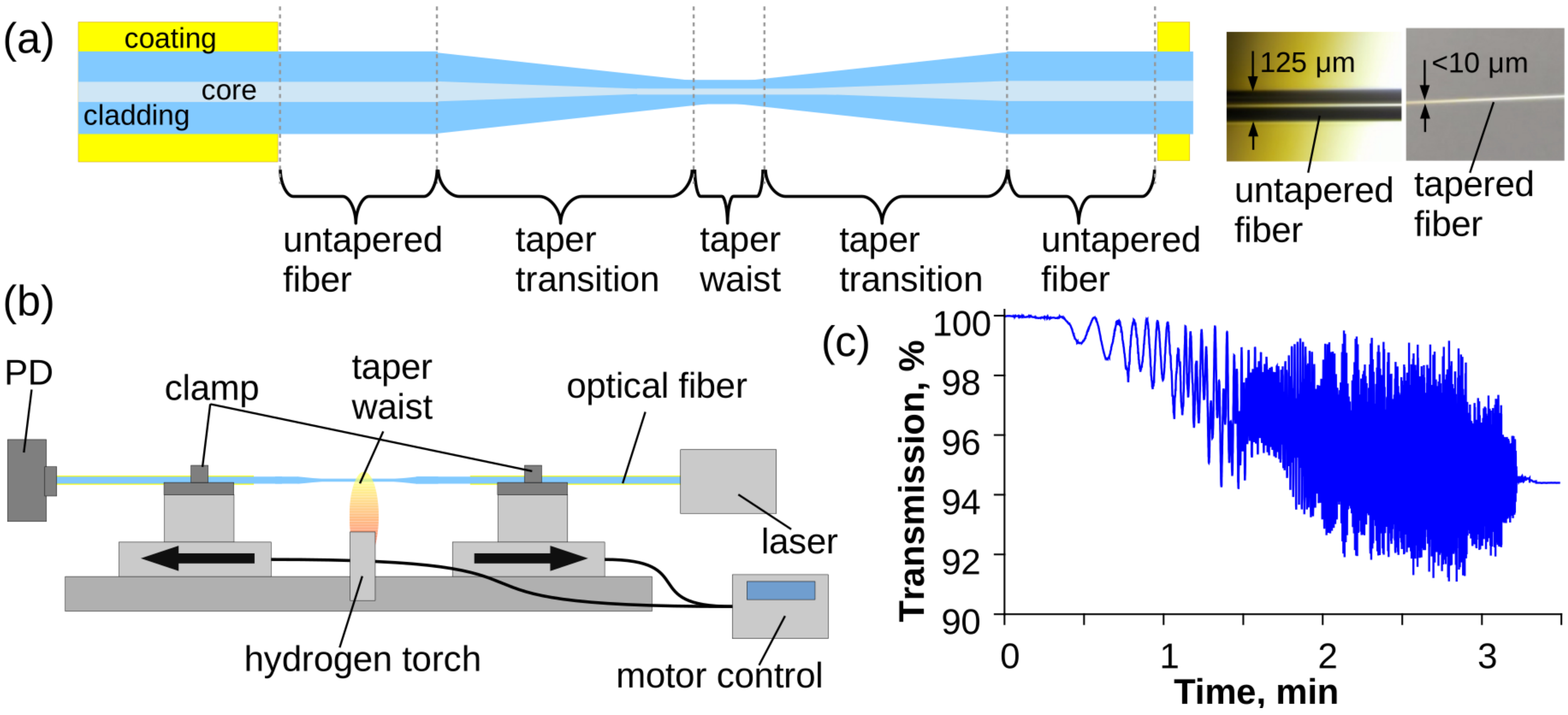




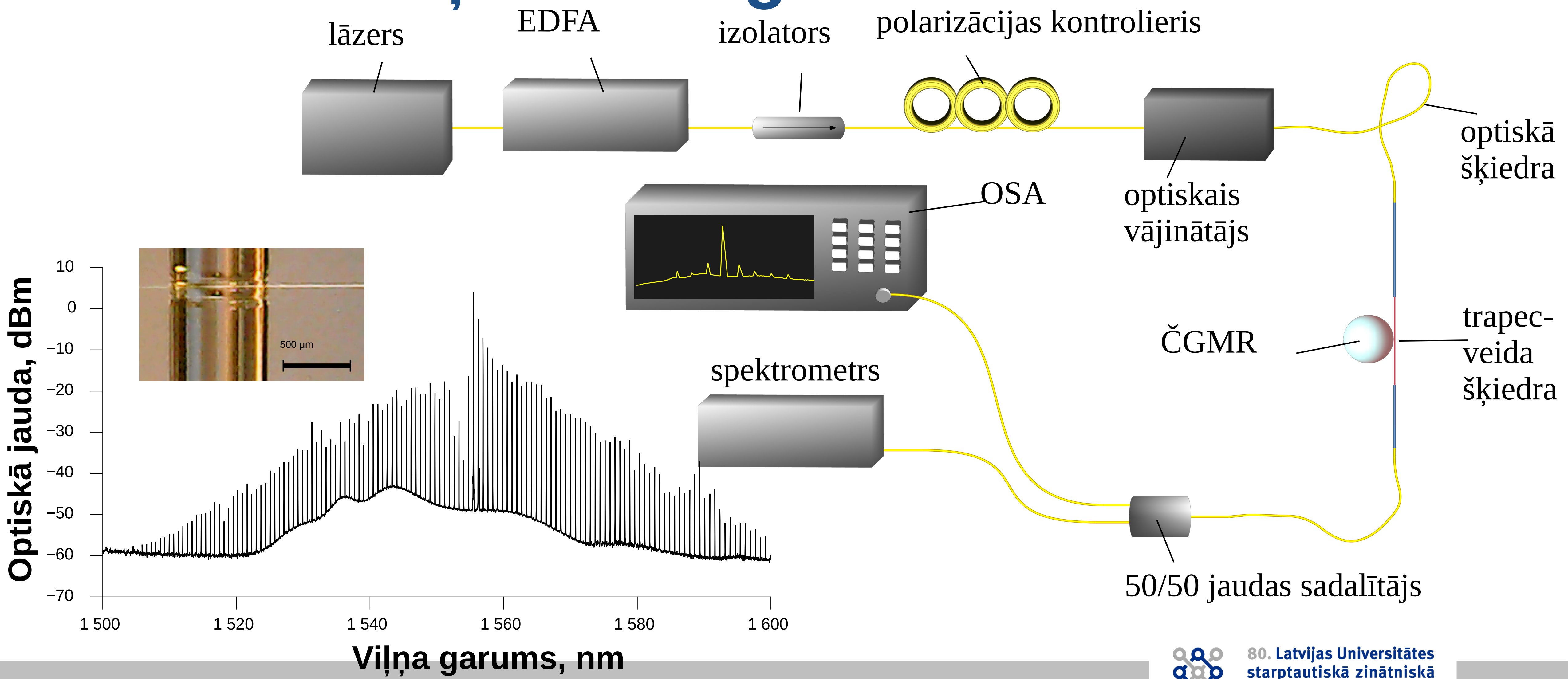




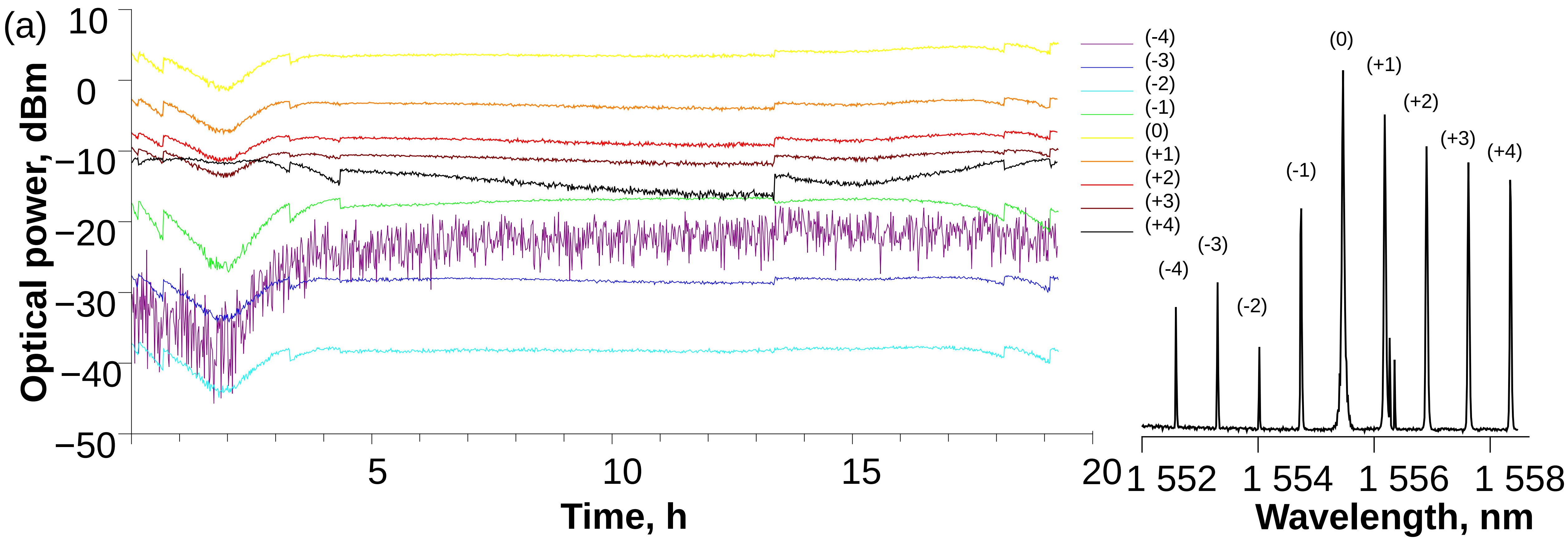
Trapecveida šķiedra



Frekvenču ķemmes ģenerēšana



Frekvenču ķemmes stabilitāte



Publikācijas

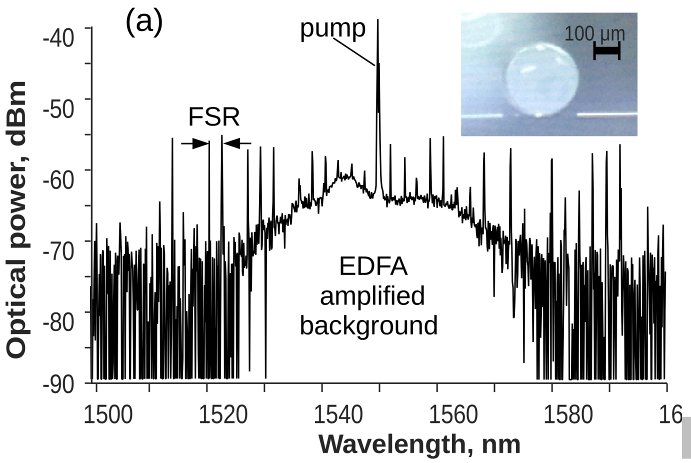
Braunfelds, J., Murnieks, R., Salgals, T., Brice, I., Sharashidze, T., Lyashuk, I., Ostrovskis, A., Spolitis, S., Alnis, J., Porins, J., Bobrovs, V., 2020. Frequency comb generation in WGM microsphere based generators for telecommunication applications. Quantum Electron. 50, 1043–1049. https://doi.org/10.1070/QEL17409

Table 1. Spatial microresonators and numerical simulations, their parameters and generated frequency combs.

Parameter	Resonator types			
	CaF_2 [1, 24]	MgF_2 [7, 8, 18, 35 38]	SiO_2 [22, 39 44]	Germanosilicate glasses [20, 21]
	Crystalline	Crystalline	Microsphere\ Microrod\ Microbubble	Microsphere
Q-factor	$(2.5\ \ 6) \times 10^9$	$(1\ \ 3) \times 10^9$	$2 \times 10^7\ \ 9.7 \times 10^8$	$1 \times 10^5\ \ 1 \times 10^7$
Radius a /mm	1.275 2.425	0.5 5.65	0.136 1	0.2 0.4
FSR /GHz	13.8 25	5.8 43	12.9 1000	
Pump wavelength λ_{pump} /nm	1550 1560	1543 1556	1549.5 1560	1550
Pump power P_{pump} /dBm	14 17	3 28.5	4.8 24.5	20
Comb width /nm	30 280	2 300	10 250	100 200
Comb spacing /GHz	13.81 359	9.9 248.5	32.6 1000	

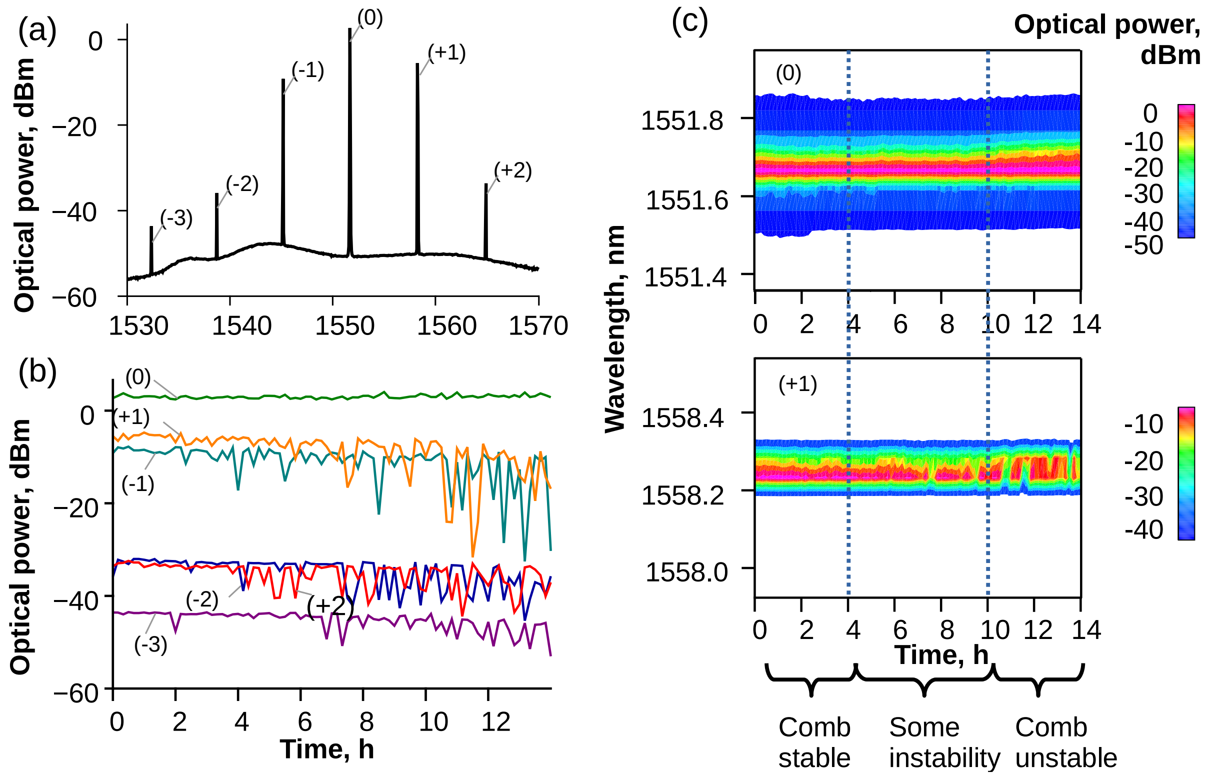
Table 2. Integrated microresonators, their parameters and generated frequency combs.

Parameter	Resonator types					
	Silica on a silicon chip [4, 50 52]	Si_3N_4 [10, 11, 14, 26, 33, 49]	AIN [47, 48]	SiN 16, 34]	Hydex glass [46]	MgF_2 [45]
	Toroidal disk	Ring	Ring	Ring	Four-port microring	Photonic belt
Q-factor	$(2\ \ 2.7) \times 10^8$	$1 \times 10^5\ \ 1.3 \times 10^6$	$(5\ \ 6) \times 10^5$	$(1\ \ 2) \times 10^6$	1.2×10^6	4.7×10^8
Radius a /mm	0.038 1	0.02 0.3	0.06	0.3	0.135	1.34
FSR /GHz	33 850	75 403	17 370	25 95.8	200	25.78
λ_{pump} /nm	1548 1560	1541 1561	1550 1553.2	1548.8 1549.4	1544.2 1558.7	1561
P_{pump} /dBm	8.8 34	21.8 34.8	27 27.8	29 34.8	17.3 18	12.8
Comb width /nm	350 1180	200 725	200		100 255	~30
Comb spacing /GHz	33 1100	17 403	370	25 95.8	32.7 6400	



Publikācijas

Brice, I., Grundsteins, K., Sedulis, A., Salgals, T., Spolitis, S., Bobrovs, V., Alnis, J., 2021. Frequency comb generation in whispering gallery mode silica microsphere resonators, in: Armani, A.M., Kudryashov, A. V., Paxton, A.H., Ilchenko, V.S., Sheldakova, J. V. (Eds.), Laser Resonators, Microresonators, and Beam Control XXIII. SPIE, p. 35. https://doi.org/10.1117/12.2577148



Publikācijas

Salgals, T., Alnis, J., Murnieks, R., Brice, I., Porins, J., Andrianov, A. V., Anashkina, E.A., Spolitis, S., Bobrovs, V., 2021. Demonstration of a fiber optical communication system employing a silica microsphere-based OFC source. Opt. Express 29, 10903. https://doi.org/10.1364/OE.419546

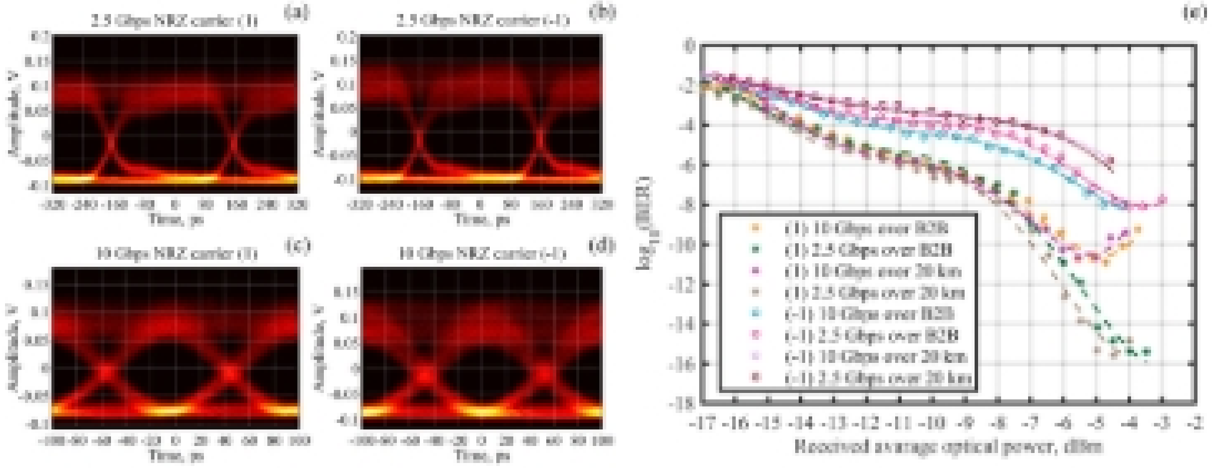


Fig. 5 Eye diagrams of the received signal after 20 km transmission over SMF fiber at a data rate of 2.5 Gbps for (a) carrier "+1" and (b) carrier "-1", and at a data rate of 10 Gbps for (c) carrier "+1" and (d) carrier "-1", and (e) the plots of BER vs. average received optical power in B2B and after 20 km transmission of the NRZ-OOK modulated signal with bitrates of 2.5 and 10 Gbps for "-1" and "+1" carriers.

Publikācijas

Spolitis, S., Murnieks, R., Skladova, L., Salgals, T., Andrianov, A. V., Marisova, M.P., Leuchs, G., Anashkina, E.A., Bobrovs, V., 2021. IM/DD WDM-PON Communication System Based on Optical Frequency Comb Generated in Silica Whispering Gallery Mode Resonator. IEEE Access 9, 66335–66345.
https://doi.org/10.1109/ACCESS.2021.3076411

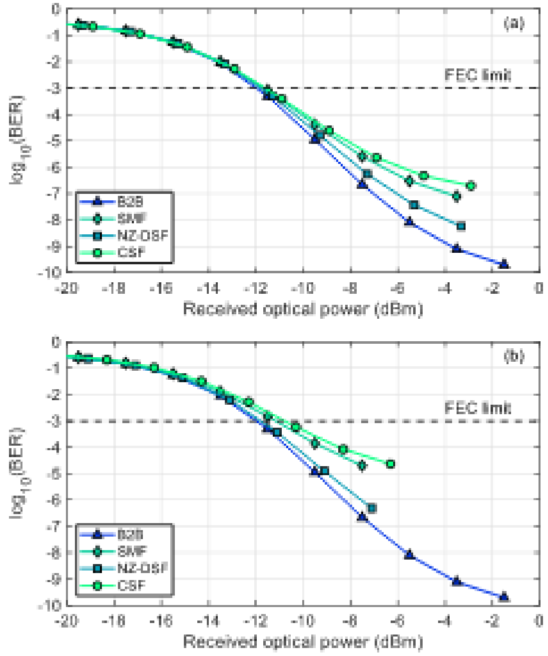


FIGURE 7. Plots of BER versus received optical power for the 10 Gbit/s per channel NRZ modulated received signals after B2B and over (a) 20 km and (b) 40 km of telecom fibers of WDM-PON transmission system with integrated OFC generator.

For objective comparison in Fig. 7, we show the BER values change with the received optical power for transmission distances 20 and 40 km. Corresponding eye diagrams of the received signal are shown only for 40 km transmission distance (Fig. 8), which is the distance reached by all fibers keeping the BER below the FEC threshold. BER curves are not plotted for 60 km transmission as the provided perfor-

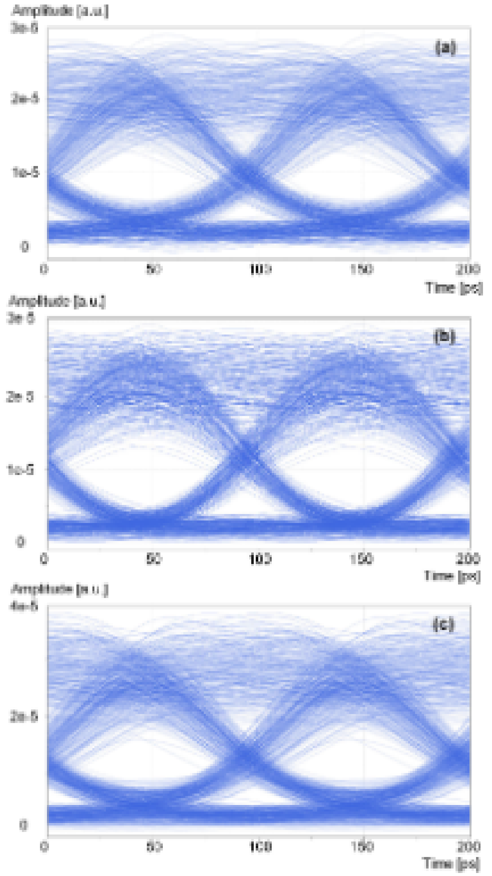


FIGURE 8. Eye diagrams of the received signal after 40 km transmission over (a) SMF, (b) NZ-DSF, and (c) CSF optical fiber link for 10 Gbit/s NRZ modulated 393 GHz spaced WDM-PON transmission system with integrated WGMR-OFC light source.

Publikācija - iesniegta

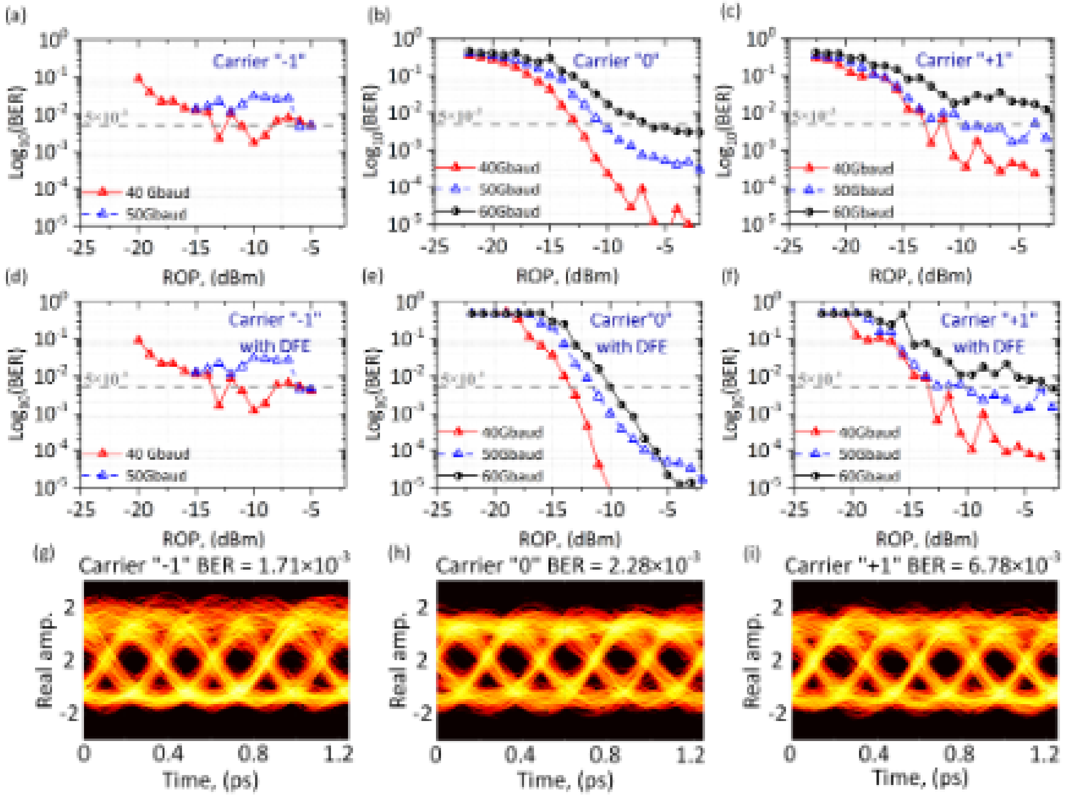


Fig. 8. BER versus ROP for the IM/DD communication system where the Kerr-OFC light source carriers "-1", "0" and "+1" can be used for NZR-OOK signals transmission with baudrates up to (a) 50 Gbaud (b) 60 Gbaud and (c) 50 Gbaud without any post-equalization. If the post-equalizer with 33-FF&15-FB taps is used, the BER is significantly improved for all these baudrates. Received signal eye diagrams for carriers: (g) "-1", (h) "0" and (i) "+1" captured at ROP of -10 dBm in the 40 Gbaud case.

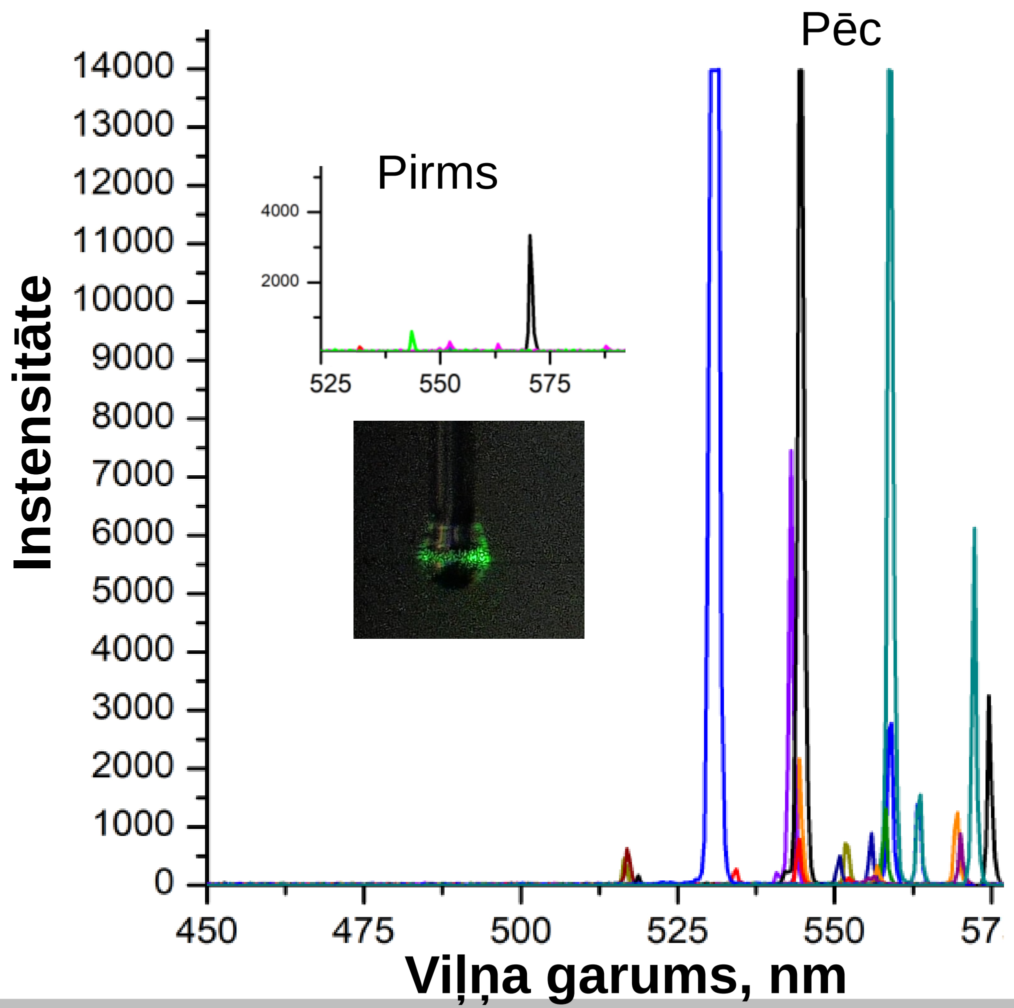
Silica microsphere WGMR-based Kerr-OFC light source and its application for high-speed IM/DD short-reach optical interconnects

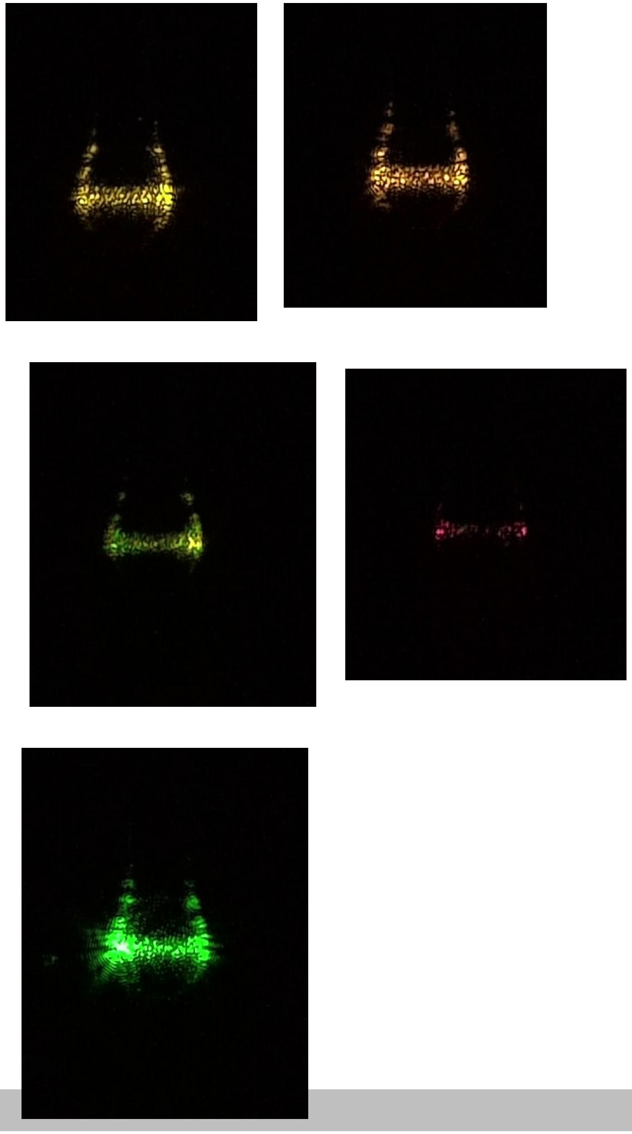
TOMS SALGALS,[1,2*] JANIS ALNIS,[3] OSKARS OZOLINS,[1,4,5] ALEXEY V. ANDRIANOV,[6] ELENA A. ANASHKINA,[6] INGA BRICE,[3] ROBERTS BERKIS,[3,7] XIAODAN PANG,[1,5] ALEKSEJS UDALCOVS,[1] JURGIS PORINS,[1] SANDIS SPOLITIS,[1,8] AND VJACESLAVS BOBROVS[1]

[1]*Institute of Telecommunications, Riga Technical University, 12 Azenes street, 1048 Riga, Latvia*
[2]*AFFOC Solutions Ltd., 17 Andrejostas street, 1045 Riga, Latvia*
[3]*Institute of Atomic Physics and Spectroscopy, University of Latvia, 3 Jelgavas street, 1004 Riga, Latvia*
[4]*Networks Unit, RISE Research Institutes of Sweden, 164 40 Kista, Sweden*
[5]*Applied Physics Department, KTH Royal Institute of Technology, 106 91 Stockholm, Sweden*
[6]*Institute of Applied Physics of the Russian Academy of Sciences, 46 Ul'yanov street,603950 Nizhny Novgorod, Russia;*
[7]*Institute for Experimental Physics, University of Innsbruck, Technikerstrasse 25, 6020 Innsbruck, Austria*
[8]*Communication Technologies Research Center, Riga Technical University, 12 Azenes street, 1048 Riga, Latvia*
*toms.salgals@rtu.lv

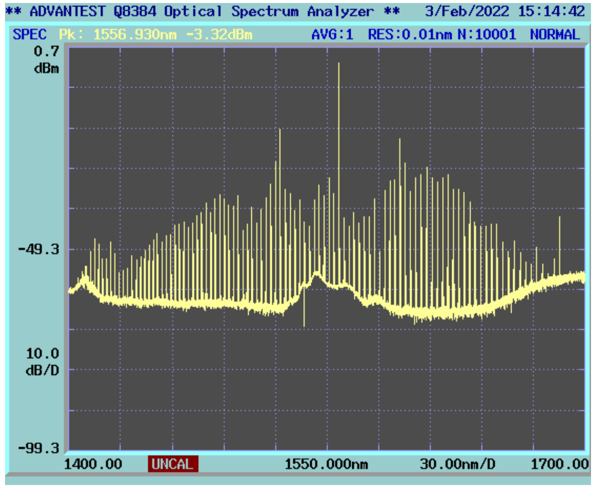
Abstract: Kerr optical frequency combs (OFC) based on silica microsphere whispering gallery mode resonator (WGMR) have various applications where they are used as a light source. For telecommunication purposes, WGMR-based Kerr-OFC comb generators can be physically realized using silica microsphere resonators and used as a replacement of multiple laser arrays. In such a realization, these novel light sources have the potential to demonstrate a new low-cost concept enabling an attractive solution for intra-datacenter interconnects (DCI). In this paper, we show an experimental demonstration of a silica microsphere WGMR-based Kerr OFC light source with 400 GHz spaced carriers and its use for data transmission employing low-cost and low-complexity intensity modulation direct detection (IM/DD) schemes. Using the non-return to zero (NRZ) on-off keying (OOK) modulation format, data rates up to 50 Gbps/λ can be used for data transmission over 2 km single-mode fiber (SMF) link. Digital equalization techniques, such as a linear equalizer with feed-forward (FF) and feedback (FB) taps, are used to improve the signal quality due to different system's distortions, including the bandwidth limitations, optical to electrical (O/E) and electrical to optical (E/O) conversions, and the link induced inter-symbol interference (ISI). Finally, we provide an insight into possible alternative technologies for intra-datacenter interconnects and investigate their limitations through transmission experiments.

Mikrosfēras pārklātas ar HgTe nanodaļiņām

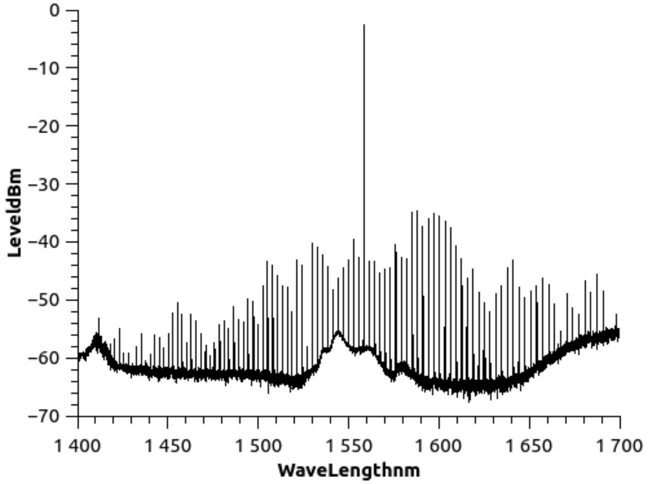




Pirms



Pēc



Paldies par uzmanību!