ERDF project

Development of optical frequency comb generator based on a whispering gallery mode microresonator and its applications in telecommunications

WGM COMB 1.1.1.1/18/A/155

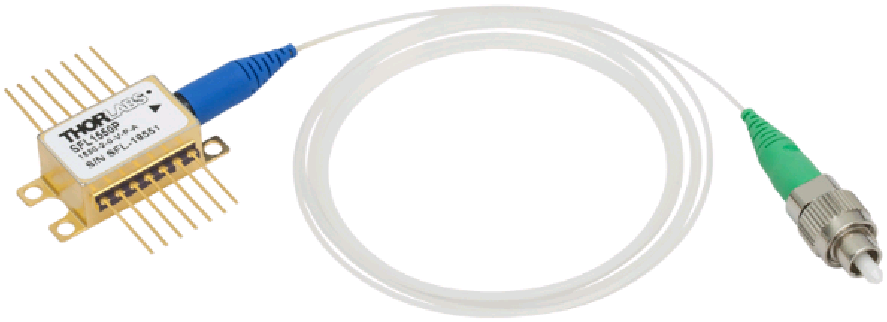
Optical fiber loop resonators

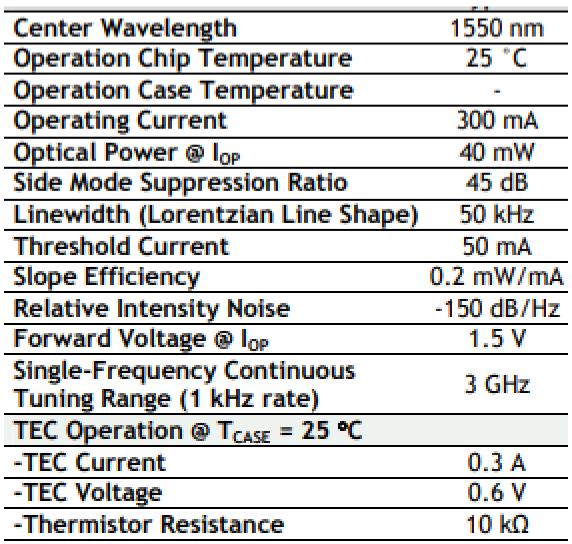
NACIONĀLAIS
ATTĪSTĪBAS
PLĀNS 2020

EIROPAS SAVIENĪBA
Eiropas Savienības
struktūrfondi un
Kohēzijas fonds

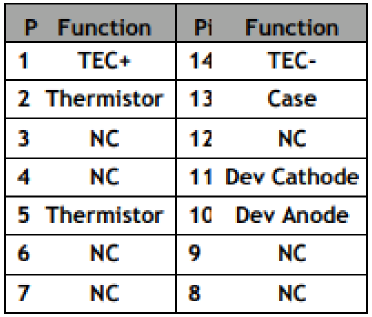
IEGULDĪJUMS TAVĀ NĀKOTNĒ

Assembling of *Thorlabs* SFL1550P - 1550 nm, 40 mW, Butterfly External Cavity Laser, PM Fiber, FC/APC frequency tuned by a current ramp

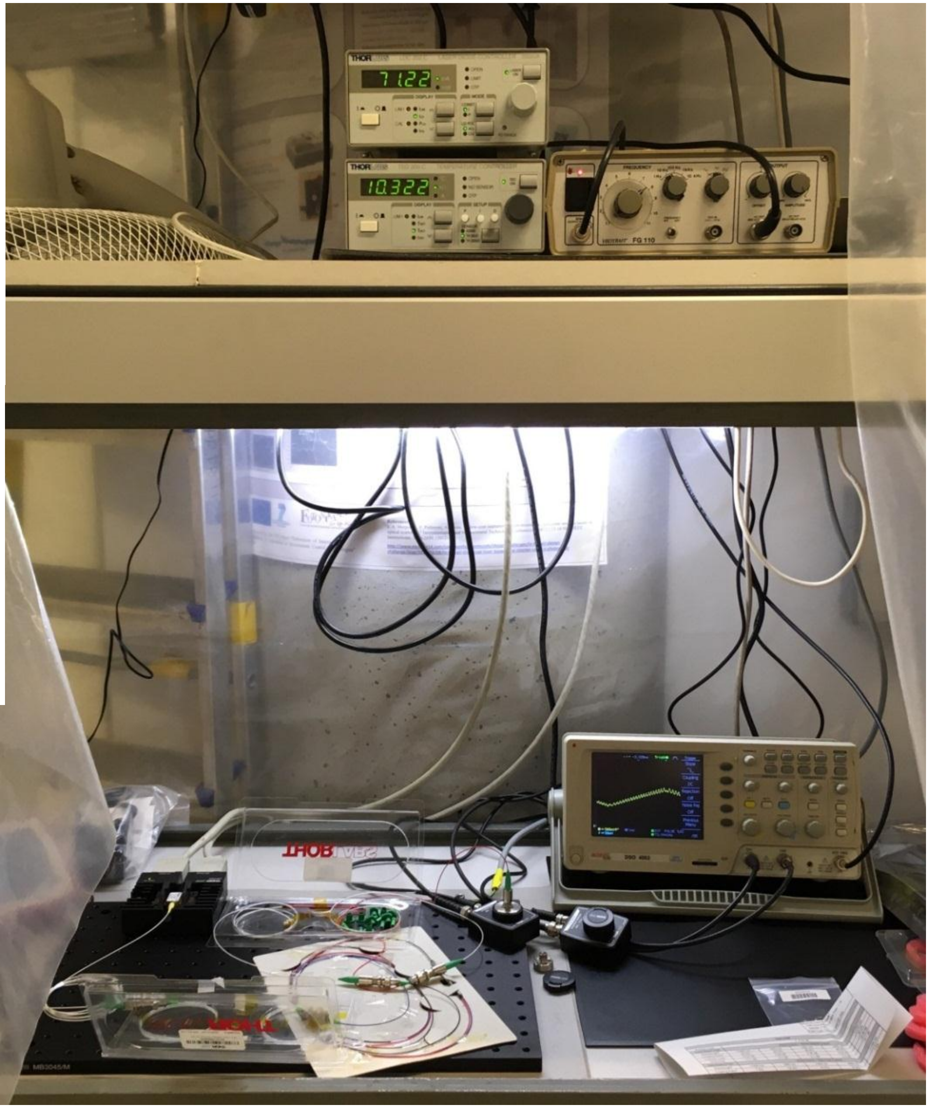




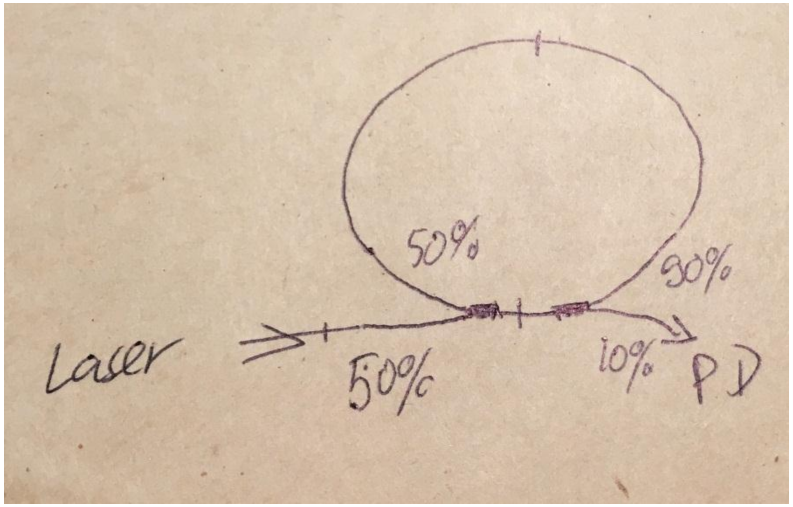
Center Wavelength	1550 nm
Operation Chip Temperature	25 °C
Operation Case Temperature	-
Operating Current	300 mA
Optical Power @ I_{OP}	40 mW
Side Mode Suppression Ratio	45 dB
Linewidth (Lorentzian Line Shape)	50 kHz
Threshold Current	50 mA
Slope Efficiency	0.2 mW/mA
Relative Intensity Noise	-150 dB/Hz
Forward Voltage @ I_{OP}	1.5 V
Single-Frequency Continuous Tuning Range (1 kHz rate)	3 GHz
TEC Operation @ T_{CASE} = 25 °C	
-TEC Current	0.3 A
-TEC Voltage	0.6 V
-Thermistor Resistance	10 kΩ



P	Function	Pi	Function
1	TEC+	14	TEC-
2	Thermistor	13	Case
3	NC	12	NC
4	NC	11	Dev Cathode
5	Thermistor	10	Dev Anode
6	NC	9	NC
7	NC	8	NC

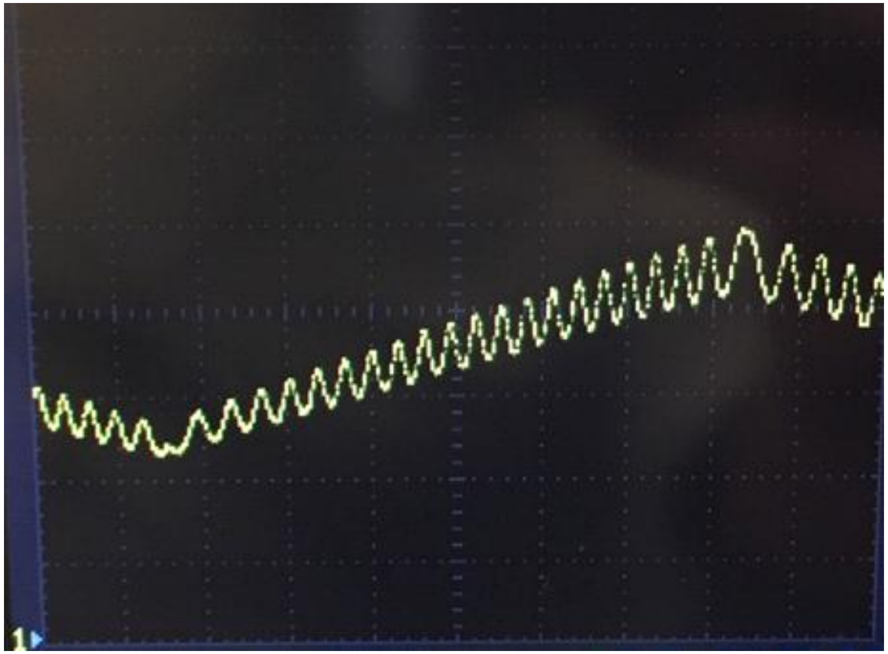


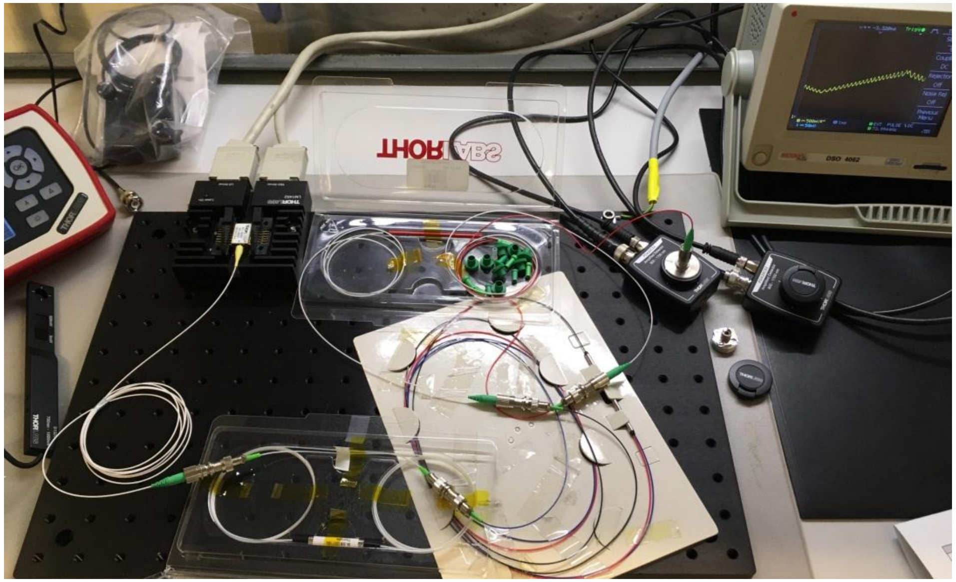
Idea to make a fiber loop resonator using two Y-type splitters
Low-finesse resonances observed



Y-type splitters are more commonly available and cheaper than X-type splitters

optica 6, 152 (2019)

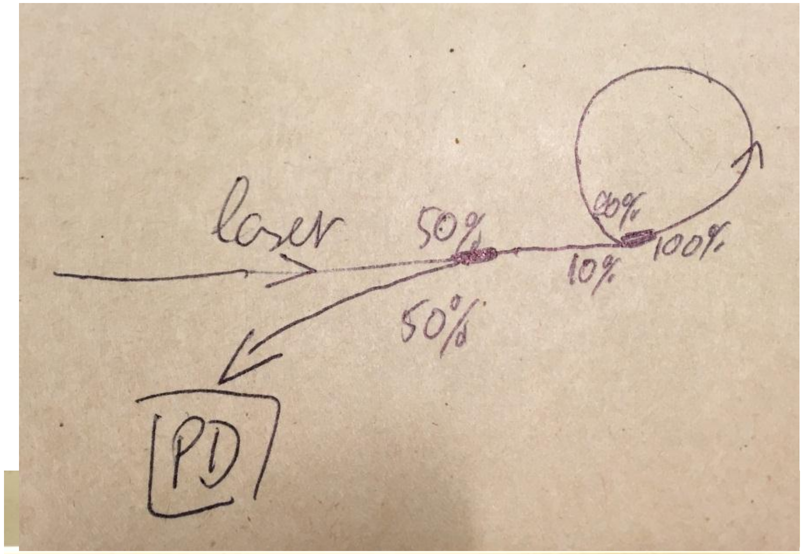


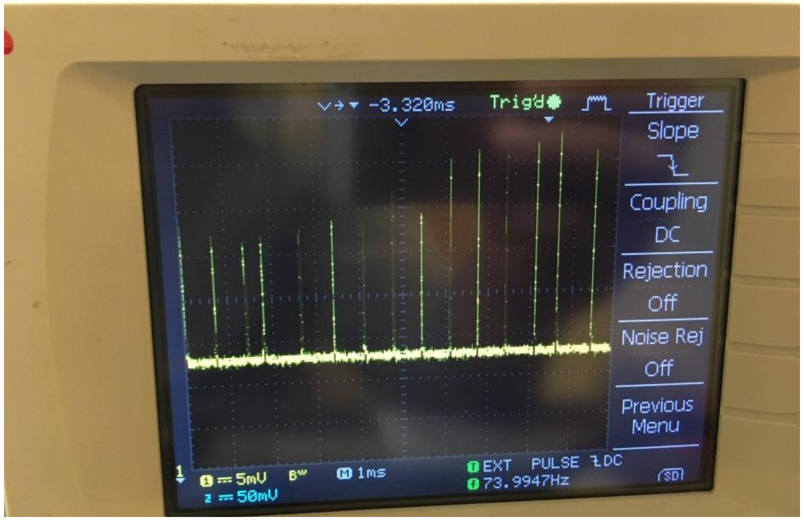


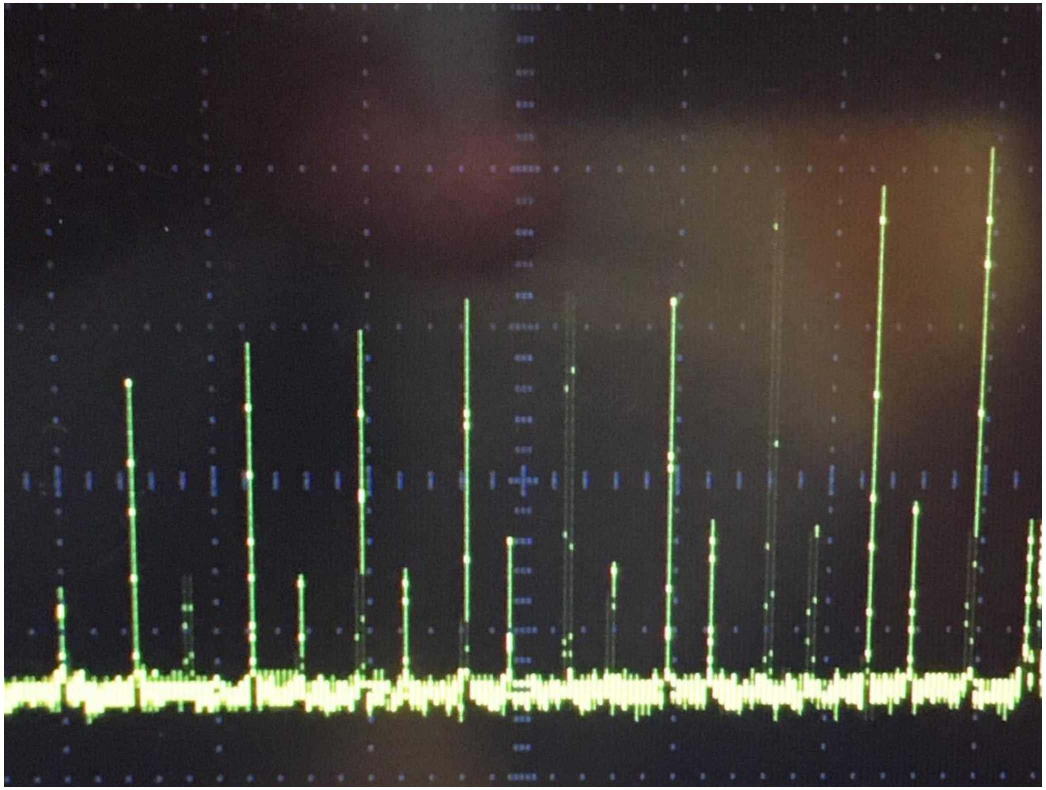
Narrow resonances using 90:10% Y-type splitter

Monitoring resonances in a weak back-reflected scattered radiation through a 50% splitter or optical circulator.

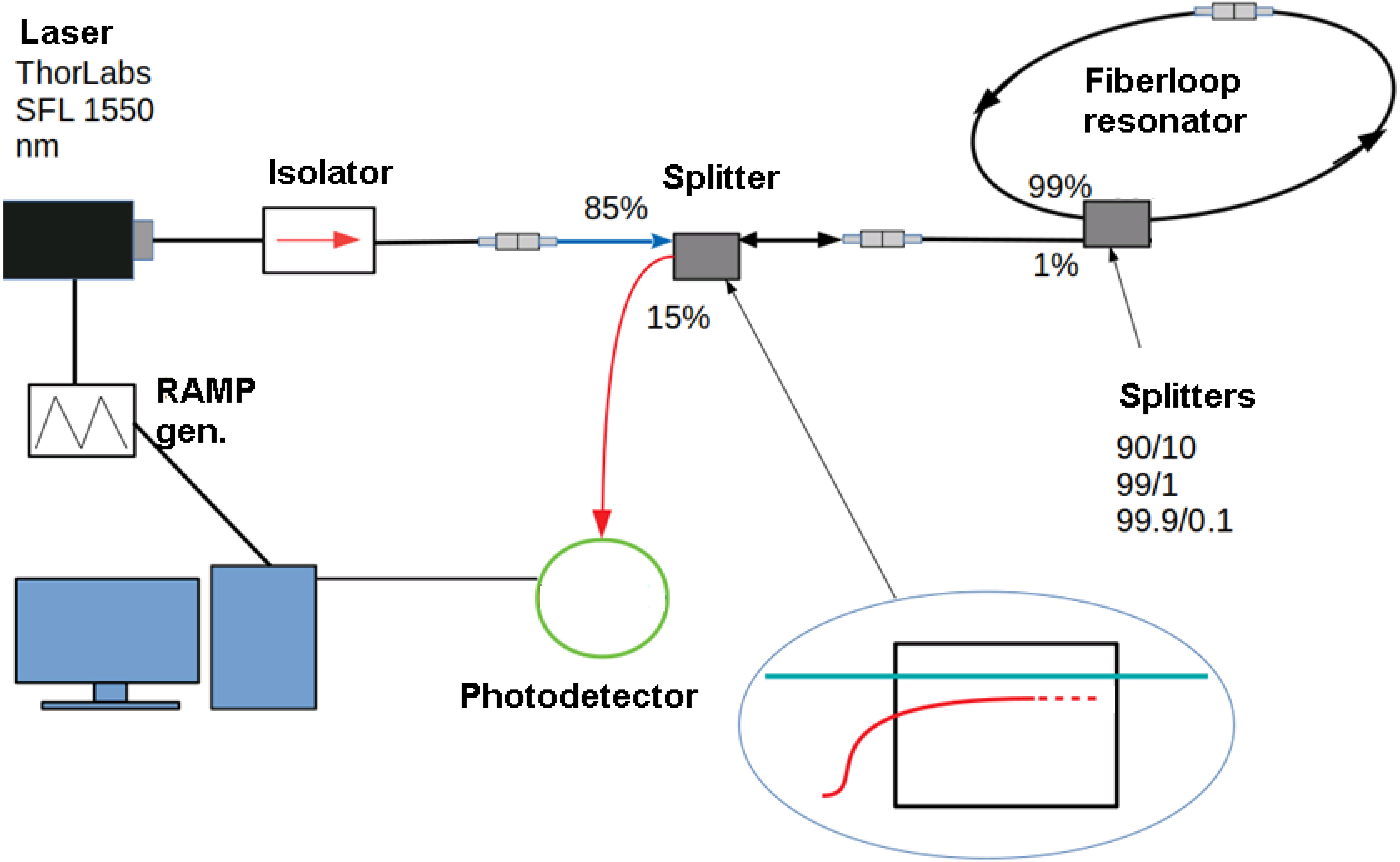
Back-returned signal goes from the imperfections of the connector inside a loop and could unreliable at low power excitation when nonlinear effects are negligible.







Experimental setup for fiberloop made from a Y-type splitter



Laser
ThorLabs
SFL 1550
nm

Isolator

Splitter

Fiberloop
resonator

RAMP
gen.

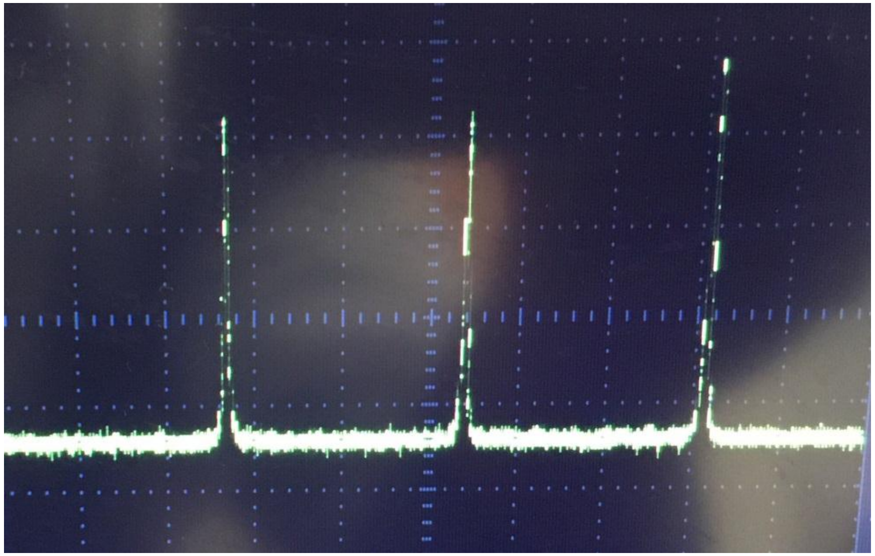
Photodetector

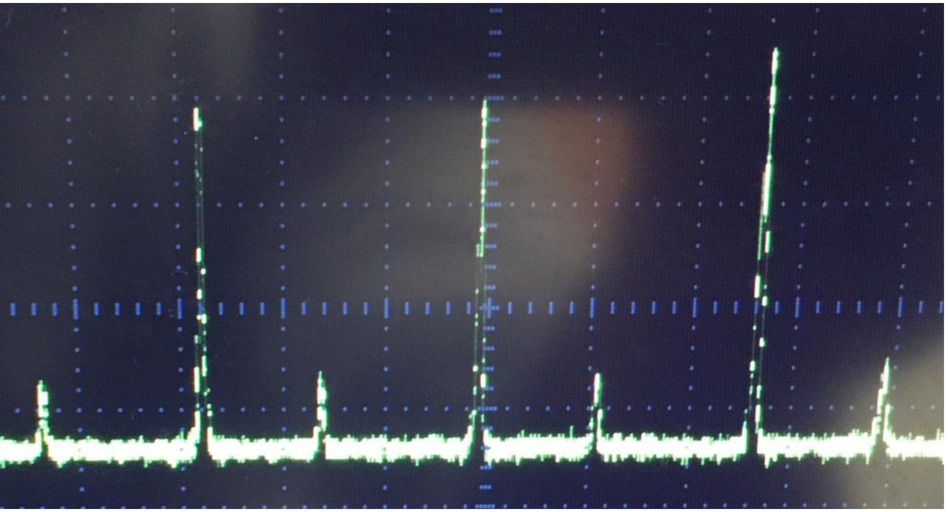
Splitters

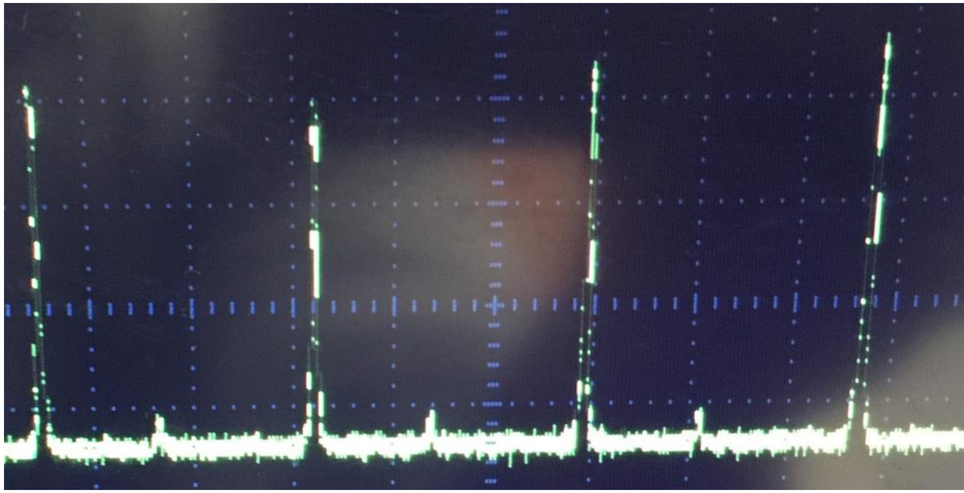
90/10
99/1
99.9/0.1

Pump laser polarisation by bending fiber allows to optimise excitation of TE or TM mode families

Why TE and TM mode families are shifted by approximately half free spectral range (FSR)?





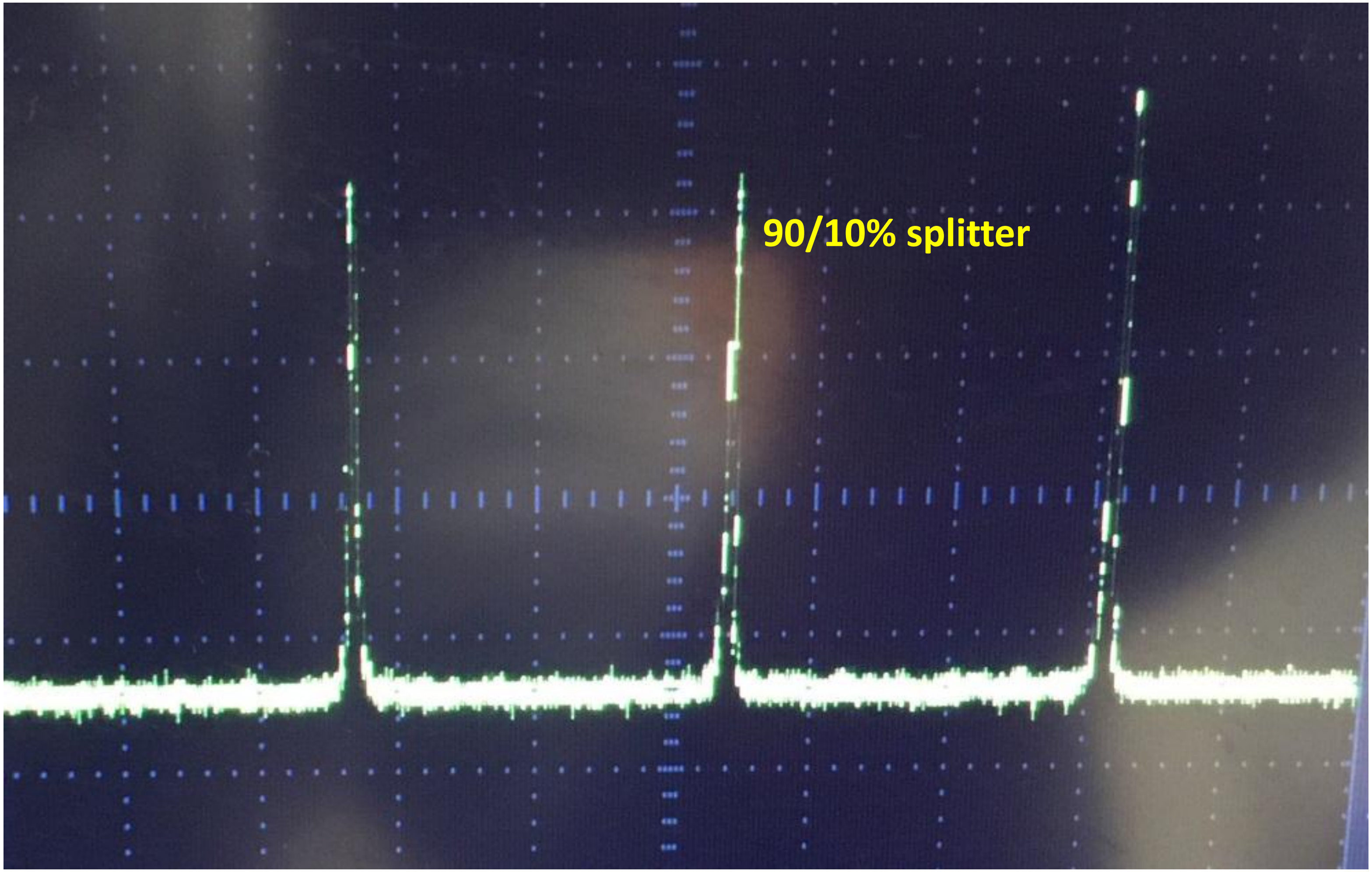


Finesse = how many peak widths fit in space between two resonances

$Finesse = 2\pi/(-ln(R)$, where R=0.9 for 90% coupler.

Finesse calculated : 59

Measured : 51



Modeling of signals adopting Fabry-Perot resonator formalism

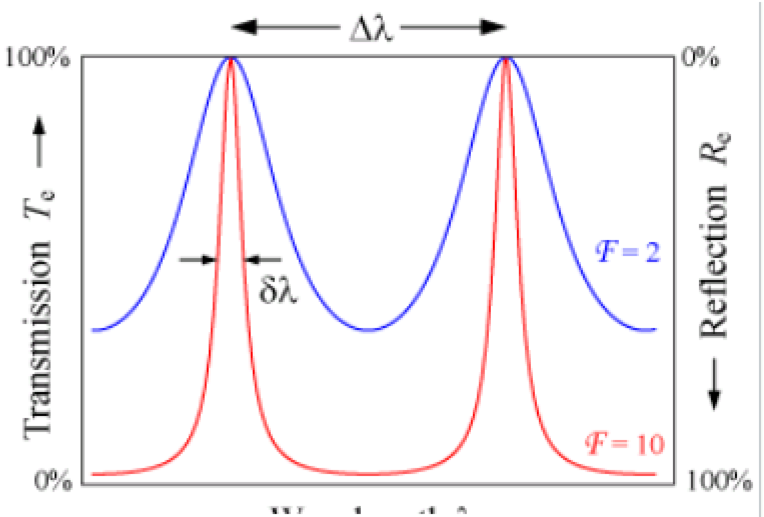
https://en.wikipedia.org/wiki/Fabry–Pérot_interferometer

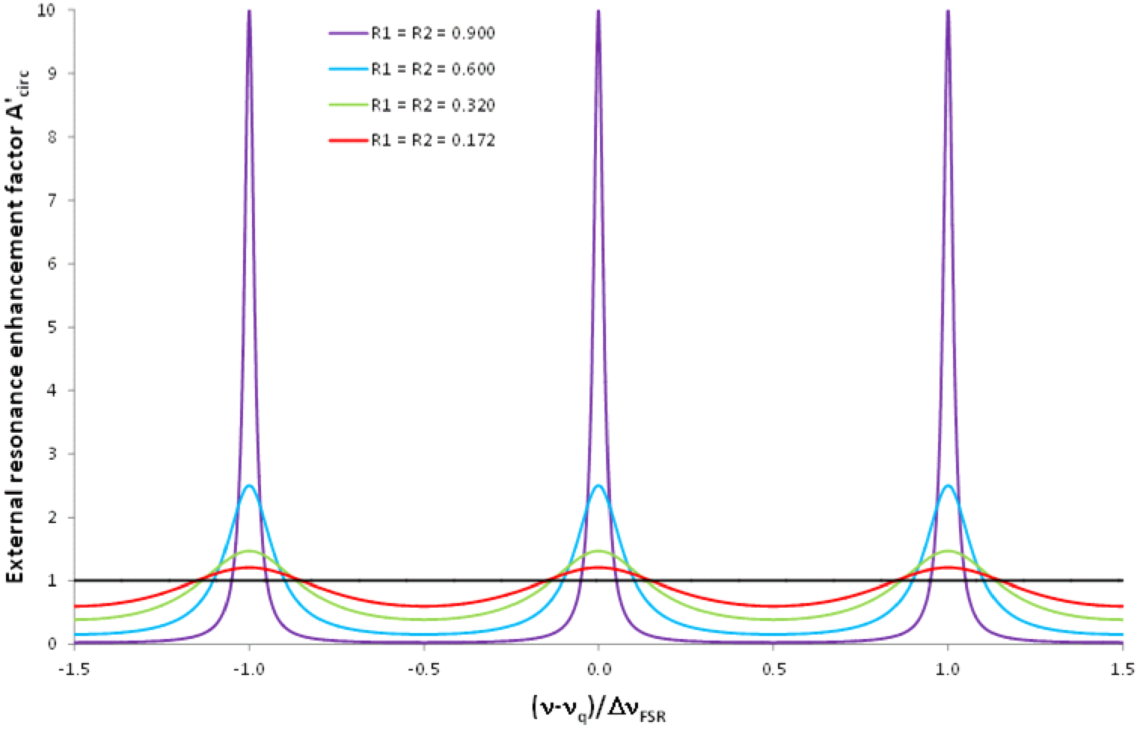
make code to generate plots using *Wolfram Mathematica*!

$$\delta = \left(\frac{2\pi}{\lambda}\right) 2n\ell\cos\theta$$

$$T_e = \frac{(1-R)^2}{1-2R\cos\delta+R^2} = \frac{1}{1+F\sin^2\left(\frac{\delta}{2}\right)}$$

$$F = \frac{4R}{(1-R)^2}$$ is the *coefficient of finesse*.

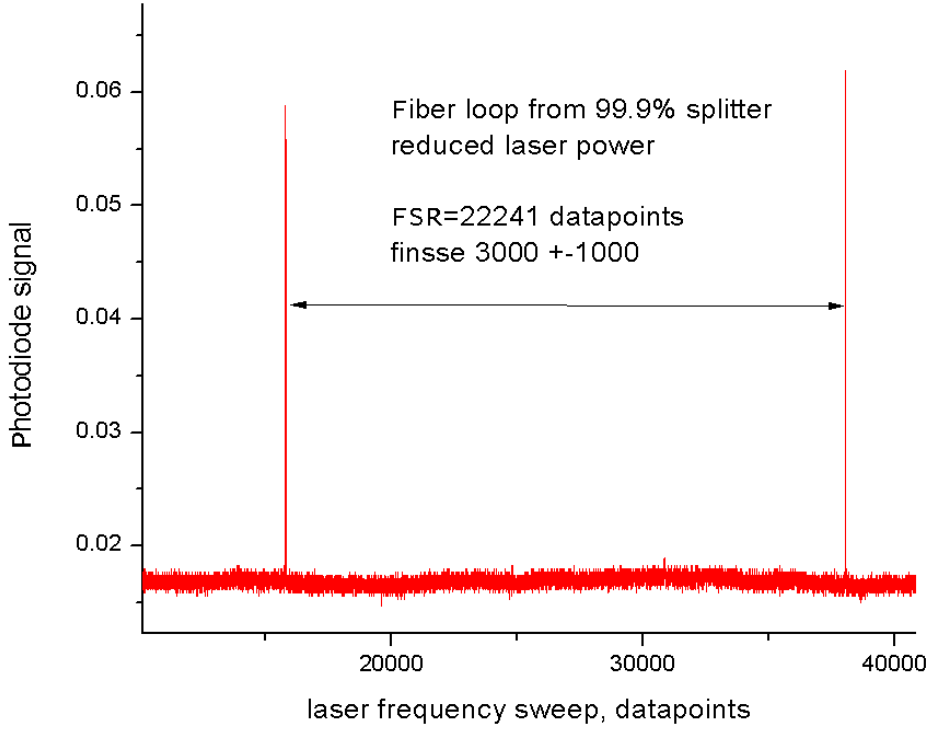




99.9:0.1 % splitter fiberloop
Measurements at possibly small pump power
to avoid nonlinear effects

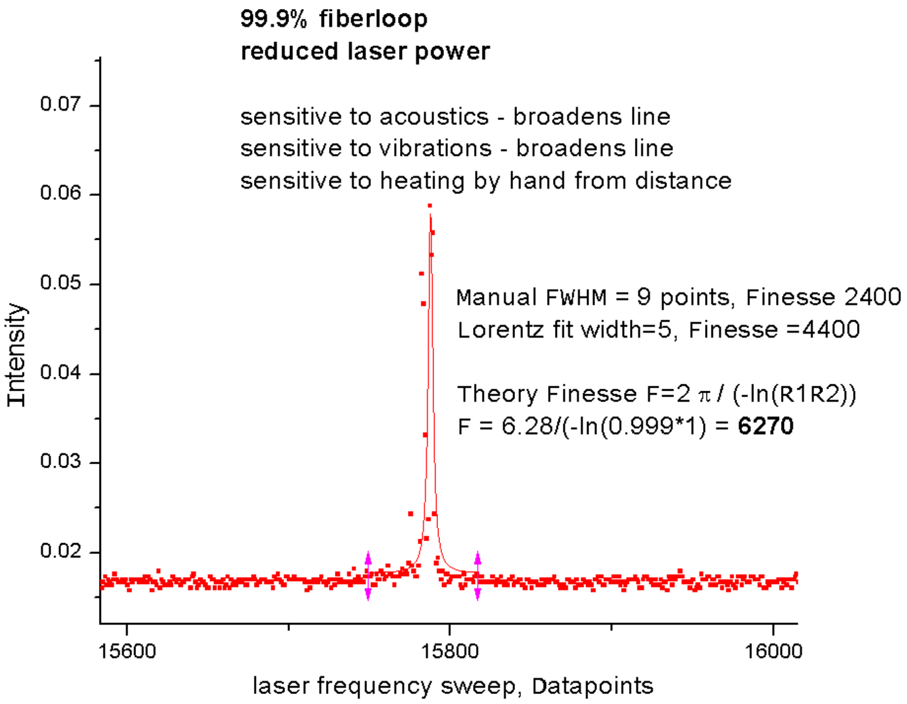
Finesse measured: 3000 ± 1000

Finesse theoretical: 6000



Fiber loop from 99.9% splitter
reduced laser power

FSR=22241 datapoints
finsse 3000 +-1000



99.9% fiberloop
reduced laser power

sensitive to acoustics - broadens line
sensitive to vibrations - broadens line
sensitive to heating by hand from distance

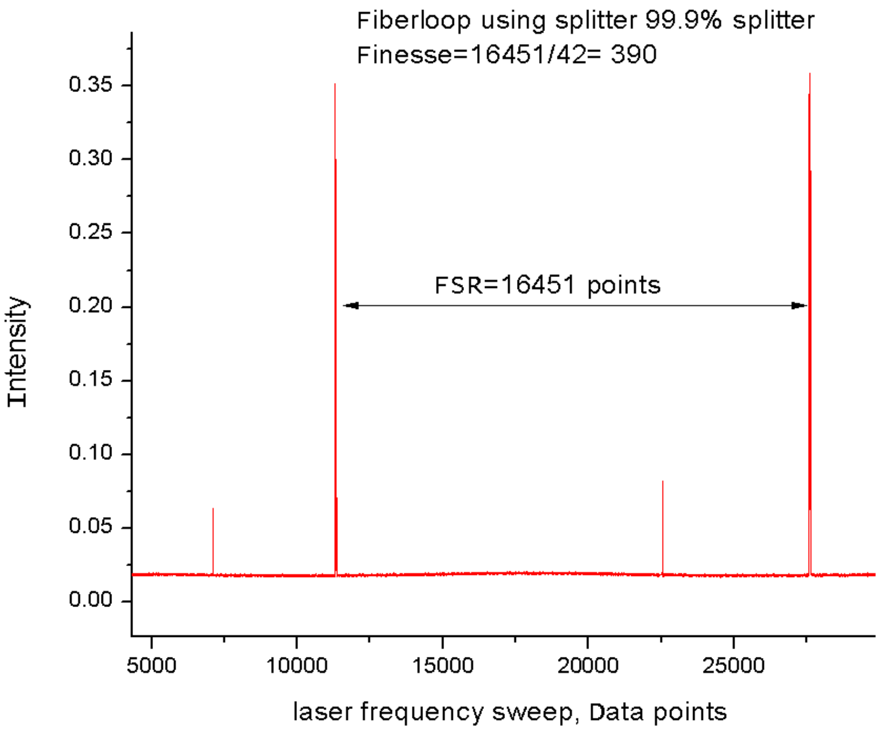
Manual FWHM = 9 points, Finesse 2400
Lorentz fit width=5, Finesse =4400

Theory Finesse F=2 π / (-ln(R1R2))
F = 6.28/(-ln(0.999*1) = **6270**

99.9:0.1 % splitter fiberloop at high pump power
can see line broadening nonlinearity by *thermal locking*

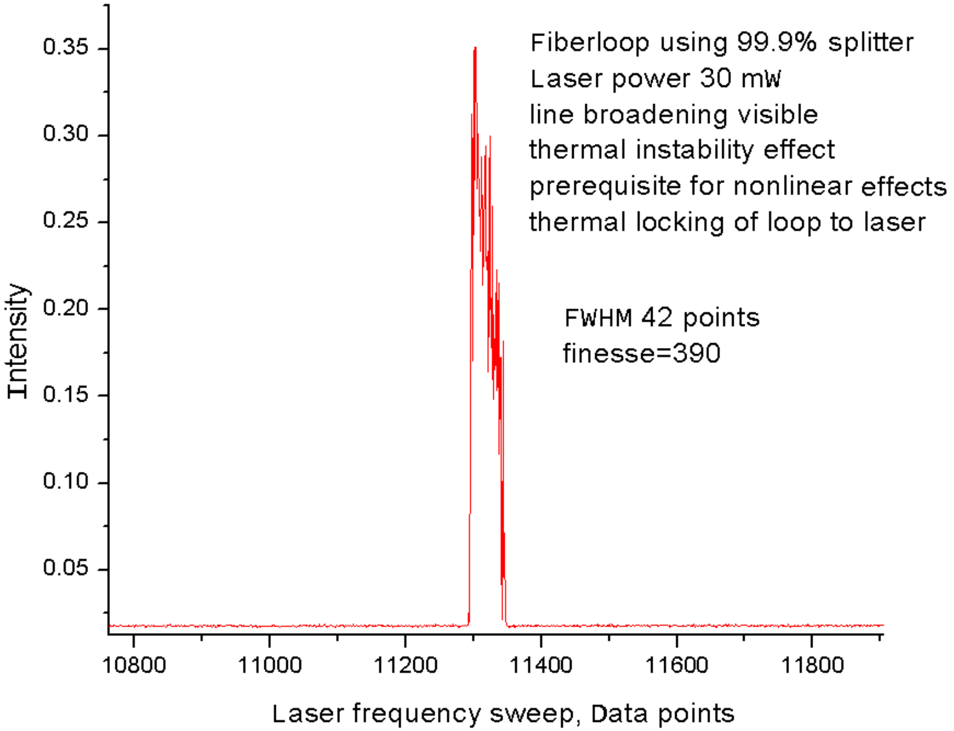
index of refraction (photorefractive) change

thermal dissipation on resonance (heating effect)



Fiberloop using splitter 99.9% splitter
Finesse=16451/42= 390

FSR=16451 points



Fiberloop using 99.9% splitter
Laser power 30 mW
line broadening visible
thermal instability effect
prerequisite for nonlinear effects
thermal locking of loop to laser

FWHM 42 points
finesse=390

Stimulated Brillouin scattering SBS in fiberloop resonator made from 90:10 % splitter

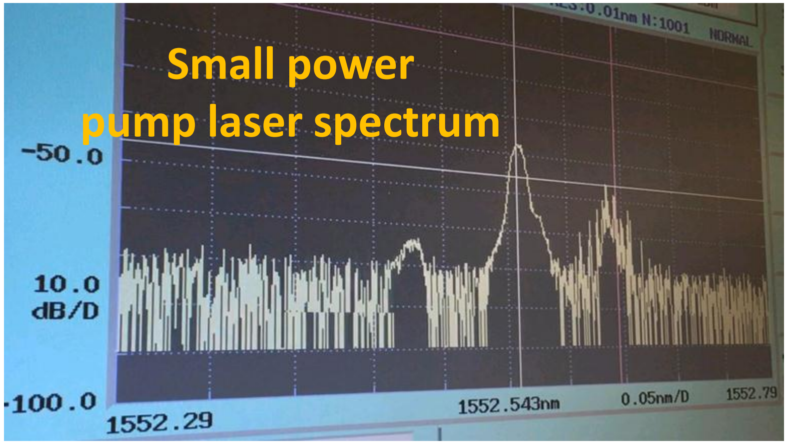
«Cobrite» laser is not fine tunable in frequency

We used 250 m HNLF in the loop
resonances should become very closely spaced and some always overlap always in resonance with the laser line.

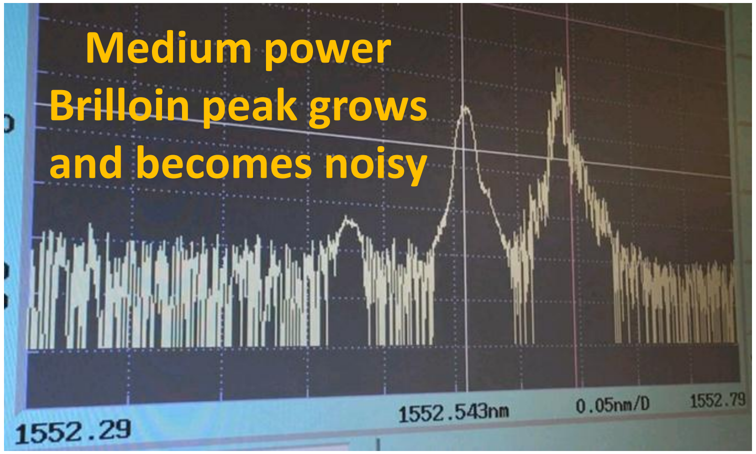
Brillouin peak is shifted ca 11GHz to lower energy in respect to the pump frequency.

Without a NHLF fiber we did not see Brillouin lasing effect, just the noise increase.

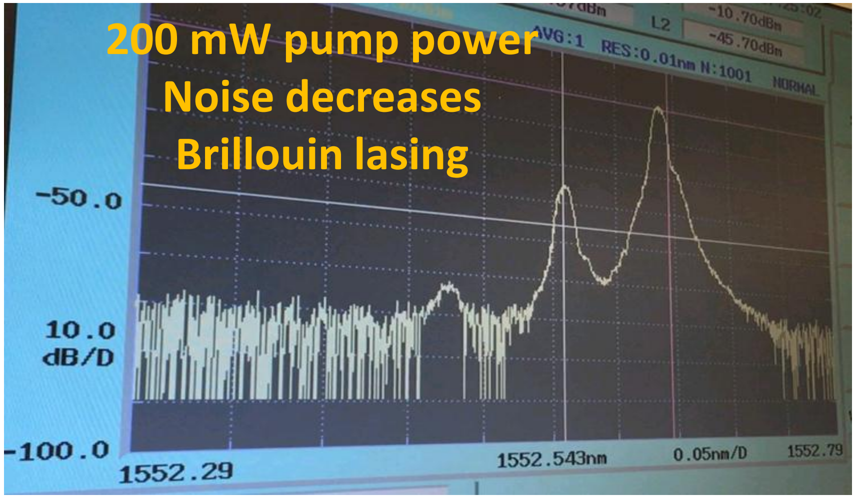
Photo OSA resolution 0.07 nm was not enough to really resolve SBS. We used *AVANTEST Q8384* OSA.
https://youtu.be/6JsGZL5qUJ8



Small power
pump laser spectrum



Medium power
Brilloin peak grows
and becomes noisy



200 mW pump power
Noise decreases
Brillouin lasing

People who make microcomb use a tunable laser

When laser frequency is fine tuned into resonance

And need around 1W pump power.

We see simiar noise

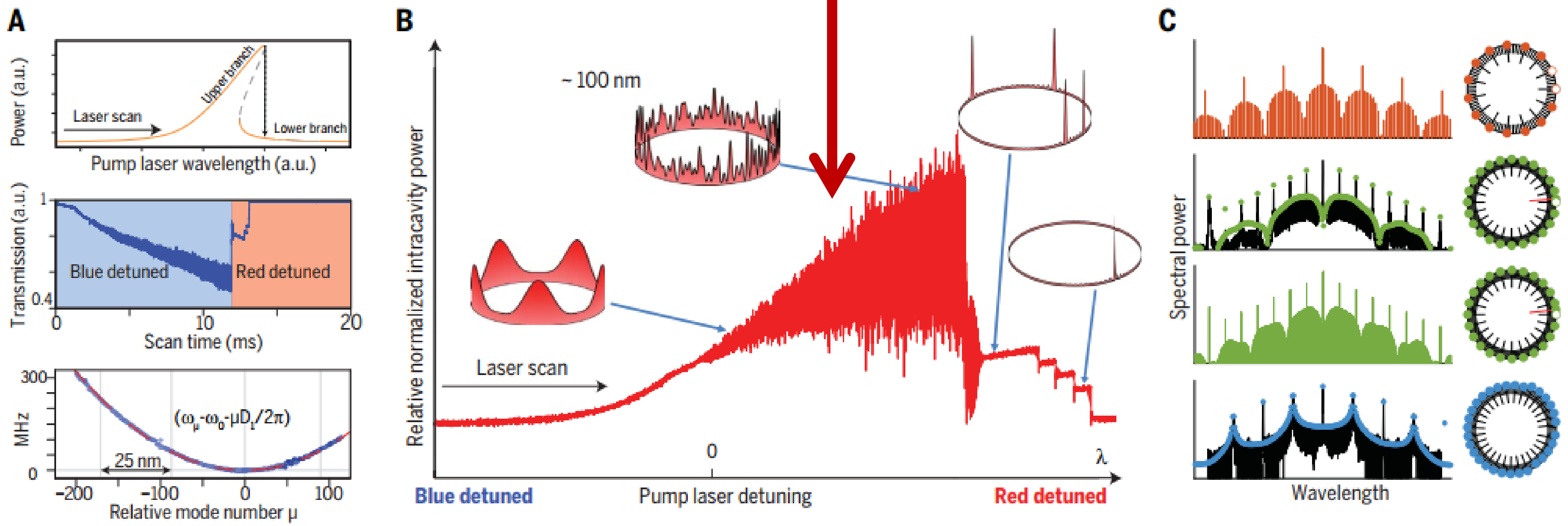


Fig. 3. Transition to the dissipative soliton states and soliton crystals. (**A**) (Top)The cavity bistability in the intra-cavity power due to the Kerr nonlinearity. (Bottom) The integrated dispersion profile [$D_{int}(\mu)$] of a measured progression of resonances exhibiting anomalous dispersion (quadratic variation of the integrated dispersion). (Middle) A series of steps on the red-detuned side of the resonance, indicative of dissipative soliton formation. (**B**) The evolution of the intracavity power as a function of laser detuning, revealing in particular a series of discrete steps associated with soliton formation. (**C**) More complex arrangements of a large number of solitons that are ordered in crystals (63, 134) but that contain defects, such as vacancies or defects. [Images are adapted from (9, 63)]

Kippenberg *et al.*, *Science* **361**, eaan8083 (2018)   10 August 2018

Microcomb community uses tunable lasers

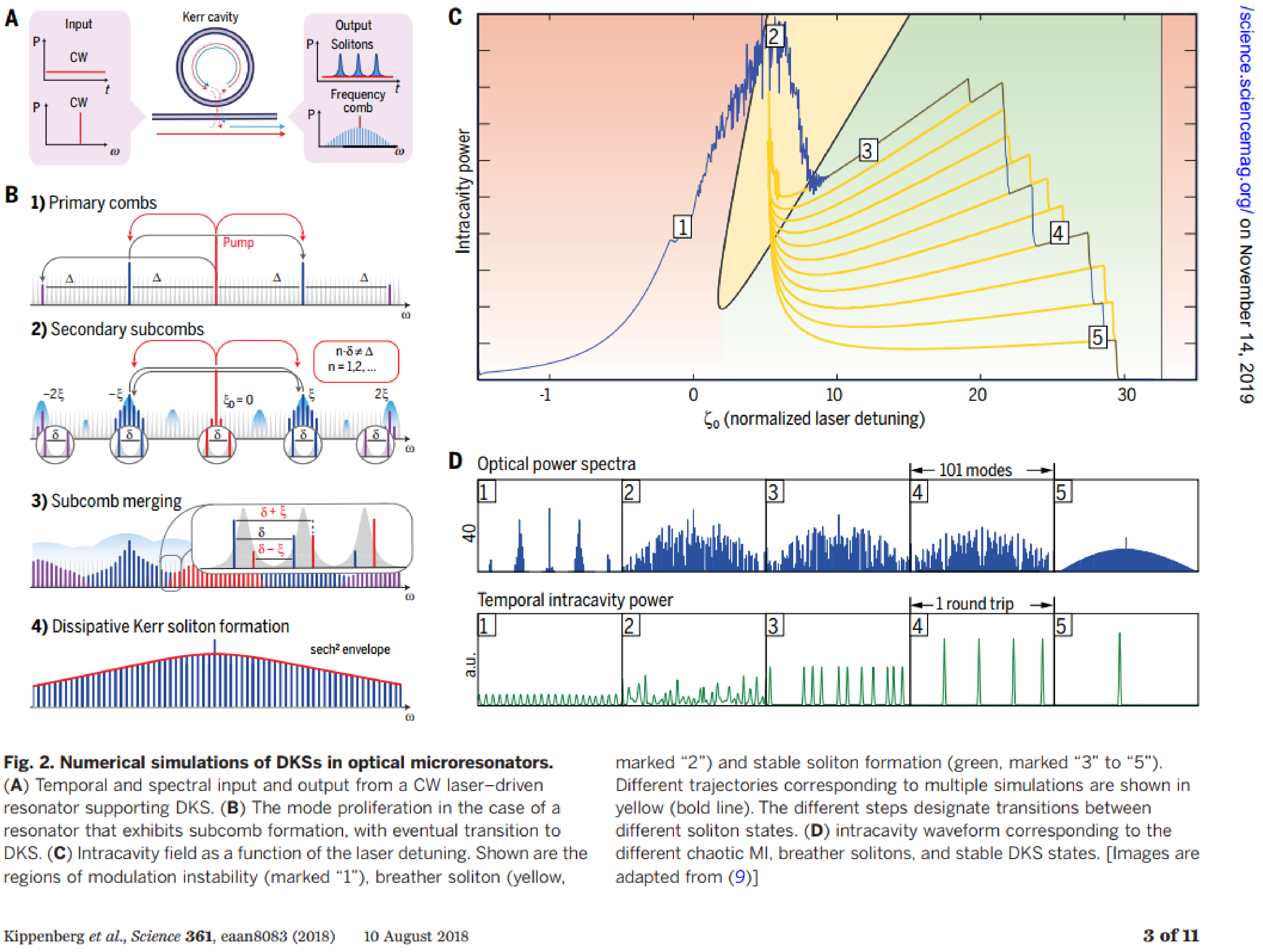


Fig. 2. Numerical simulations of DKSs in optical microresonators. (**A**) Temporal and spectral input and output from a CW laser–driven resonator supporting DKS. (**B**) The mode proliferation in the case of a resonator that exhibits subcomb formation, with eventual transition to DKS. (**C**) Intracavity field as a function of the laser detuning. Shown are the regions of modulation instability (marked "1"), breather soliton (yellow, marked "2") and stable soliton formation (green, marked "3" to "5"). Different trajectories corresponding to multiple simulations are shown in yellow (bold line). The different steps designate transitions between different soliton states. (**D**) intracavity waveform corresponding to the different chaotic MI, breather solitons, and stable DKS states. [Images are adapted from (9)]

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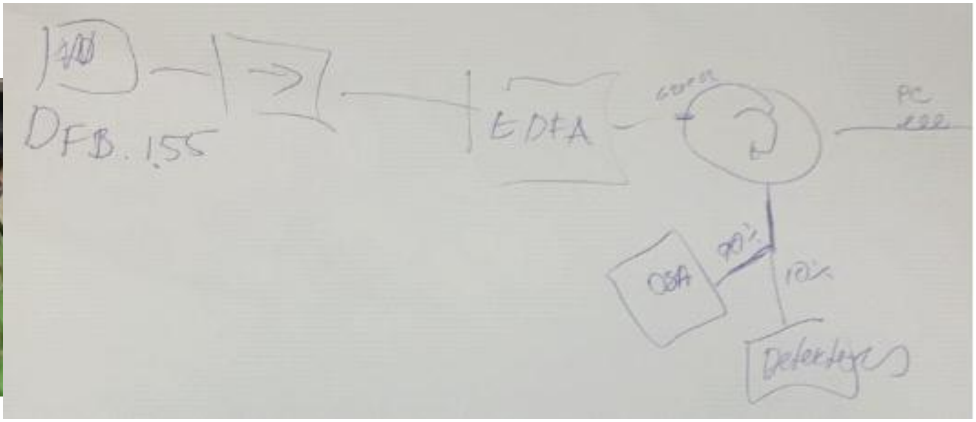
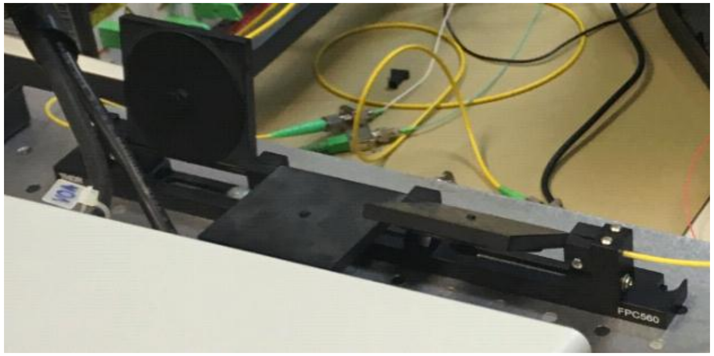
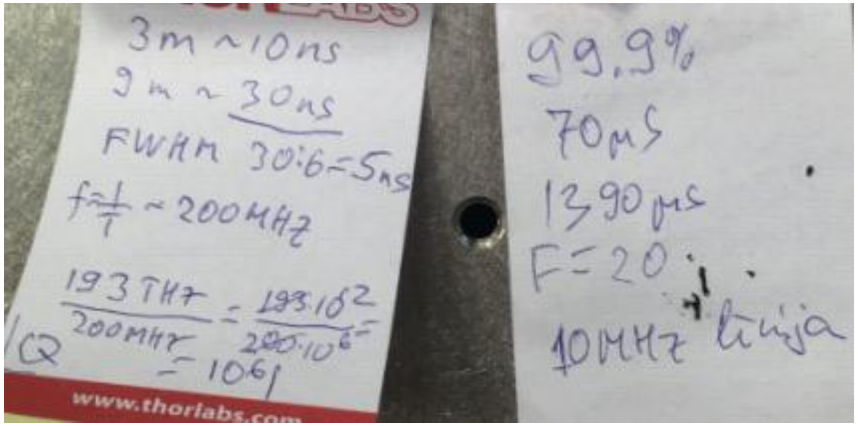
Tuneable 1.55µm DFB laser (scanned by a linear current ramp)
Power 0.5 mW hitting the loop.



```
-688us      28.8mV
-18.7ms     41.6mV
Δ18.1ms    Δ13.6mV
dV/dt       -751mV/s

Frequency 1.919kHz   Frequency 1.919kHz   RMS 25.2mV
```





3m ~ 10ns

9m ~ 30ns

FWHM 30:6 = 5ns

$f = \frac{1}{T} \sim 200MHz$

$Q = \frac{193THz}{200MHz} = \frac{193\cdot 10^{12}}{200\cdot 10^{6}} = 10^{6}$

99.9%

70µs

1390µs

F = 20

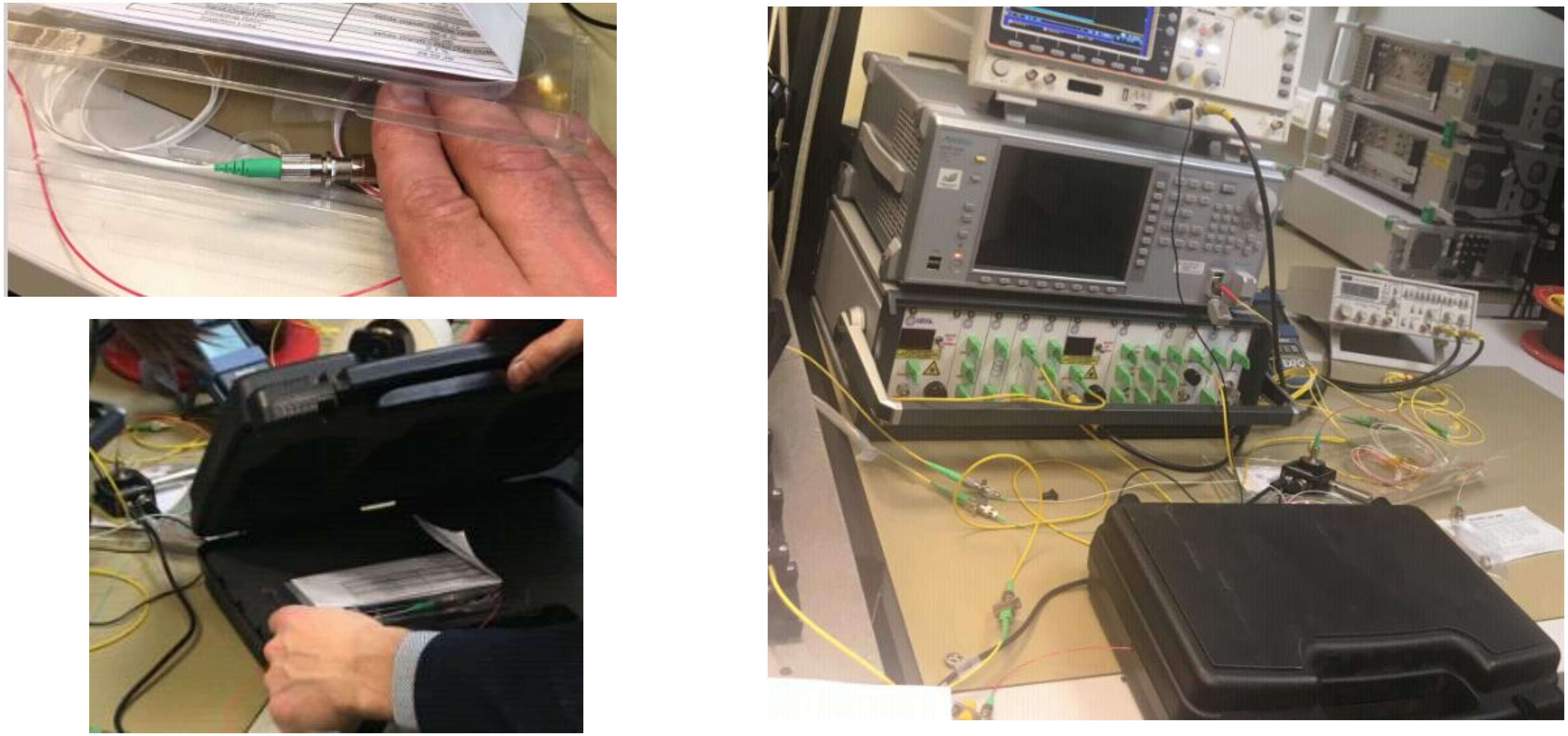
10MHz linija

All resonators are temperature sensitive

DFB laser frequency stabilises after ca 10 minutes being ON. It has a Peltier.

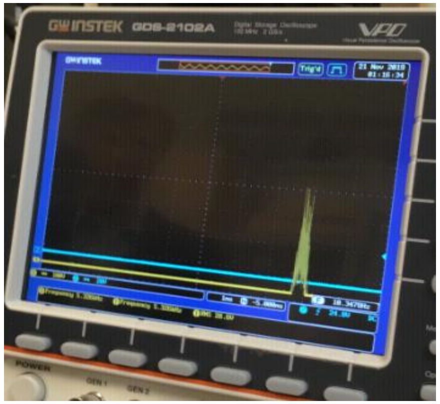
Fiberloop we placed in a Black box with foam.
Stability of a few seconds on resonance is needed to take a spectrum with optical spectrum analyser (OSA).

In Munich fiber interferometer was put inside an aluminum box covered with PU foam.
Prof. Vahala group stabilises micro-ring with a Peltier.

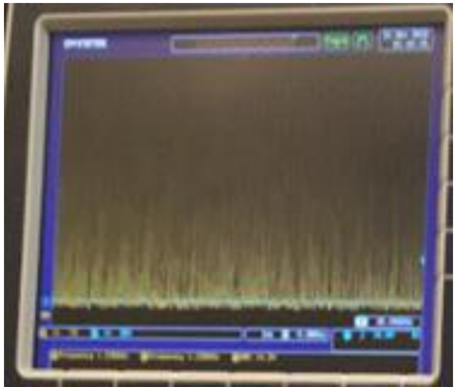


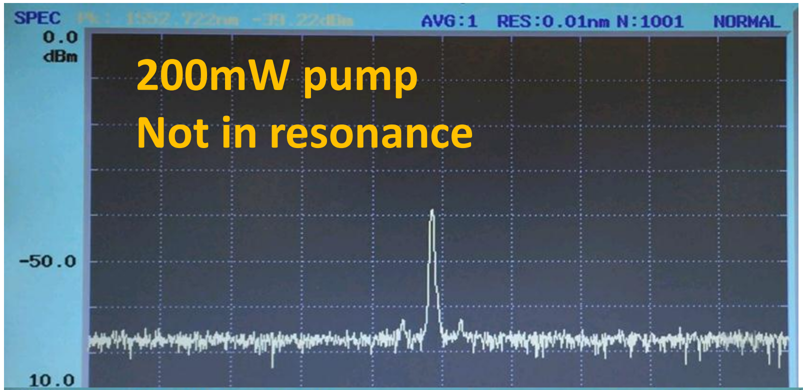
99.9:0.1 % splitter loop
Pump power 200 mW

Scanning DFB laser over resonance clearly shows broadening.

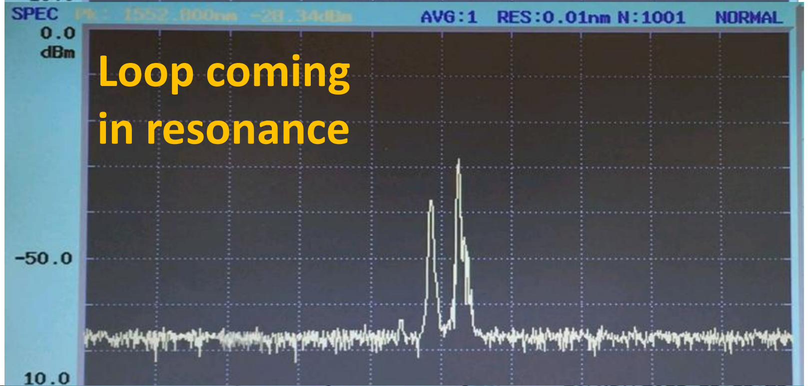


OSA needs about 1 s to take spectrum.
For OSA measurements laser current scan was switched off.
Due to thermal drift resonance shifts in and away within a few seconds.

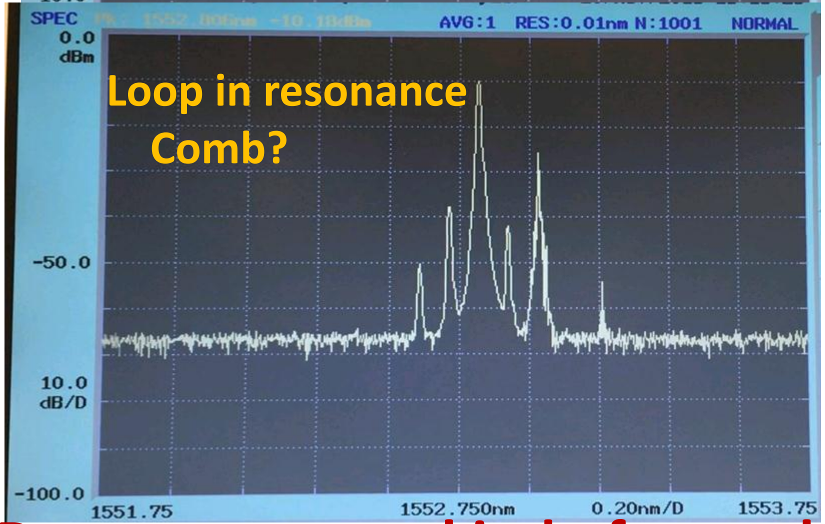




200mW pump
Not in resonance



Loop coming in resonance



Loop in resonance
Comb?

Do we see some kind of a comb?

https://youtu.be/Q0ljzhFKKEk

Why can not find publications on fiberloop Kerr combs?

For our 99.9:0.1% fiberloop we measure *Q* factor *ca* 1E6.
Theoretically, if *Q* factor is limited by SiO_2 material absorption it does not matter how long is the ring (loop or microresonator) and 1E8 should be attainable.

Why microresonator combs work, but have not seen publications on fiberloop combs?

Publications on fiberloop combs (frep 5 or 10GHz) all use an in-loop EOM modulator.

In fiberloop pipe is longer but energy flow density should be same as in microring.
In fiberloop heat dissipates in large volume, but microresonator heats up more severe locally causing thermal locking of resonance to a pump laser line.

Nice pictures from a publication in *Nature. How they draw them?*

To get a publication in *Nature nowadays* need microfabrication