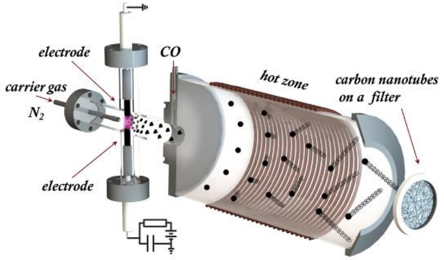
Генерация оптических гребенок на волоконных лазерах со встроенными оптическими микрорезонаторами

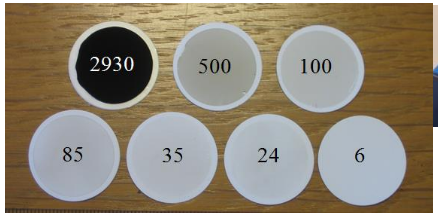
Юрий Гладуш

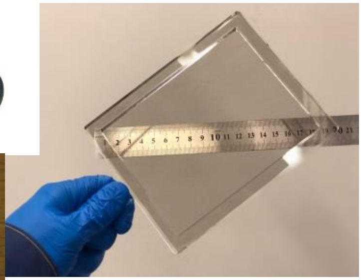
Лаборатория Наноматериалов
Сколтех

Laboratory of Nanomaterials

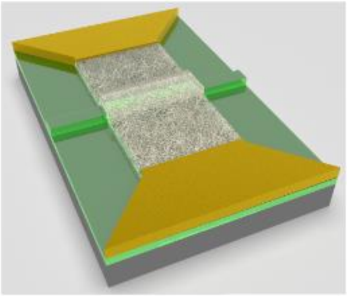
Carbon nanotubes



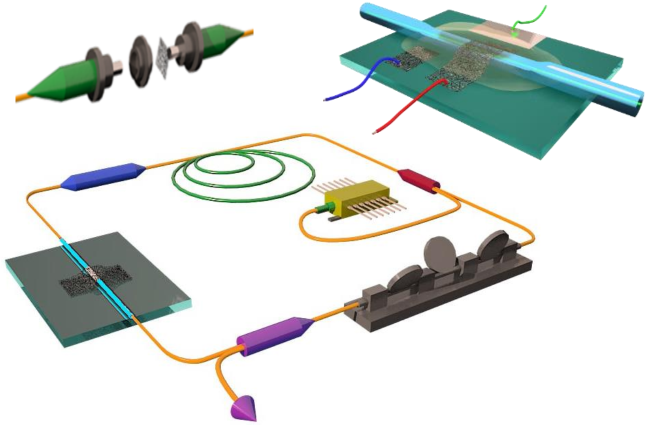




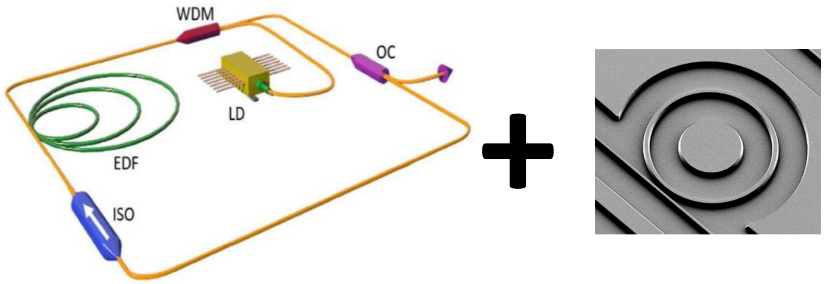
Integrated optical devices: wavelength convertors, photodetectors



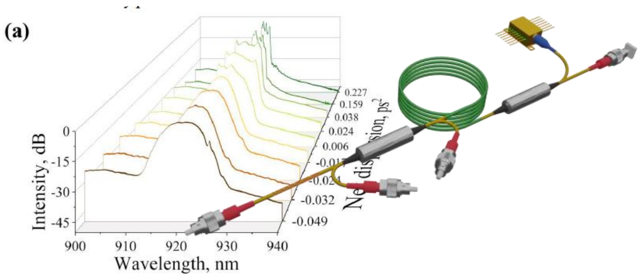
Ultrafast fiber lasers



Fiber lasers with integrated high-Q microcavity

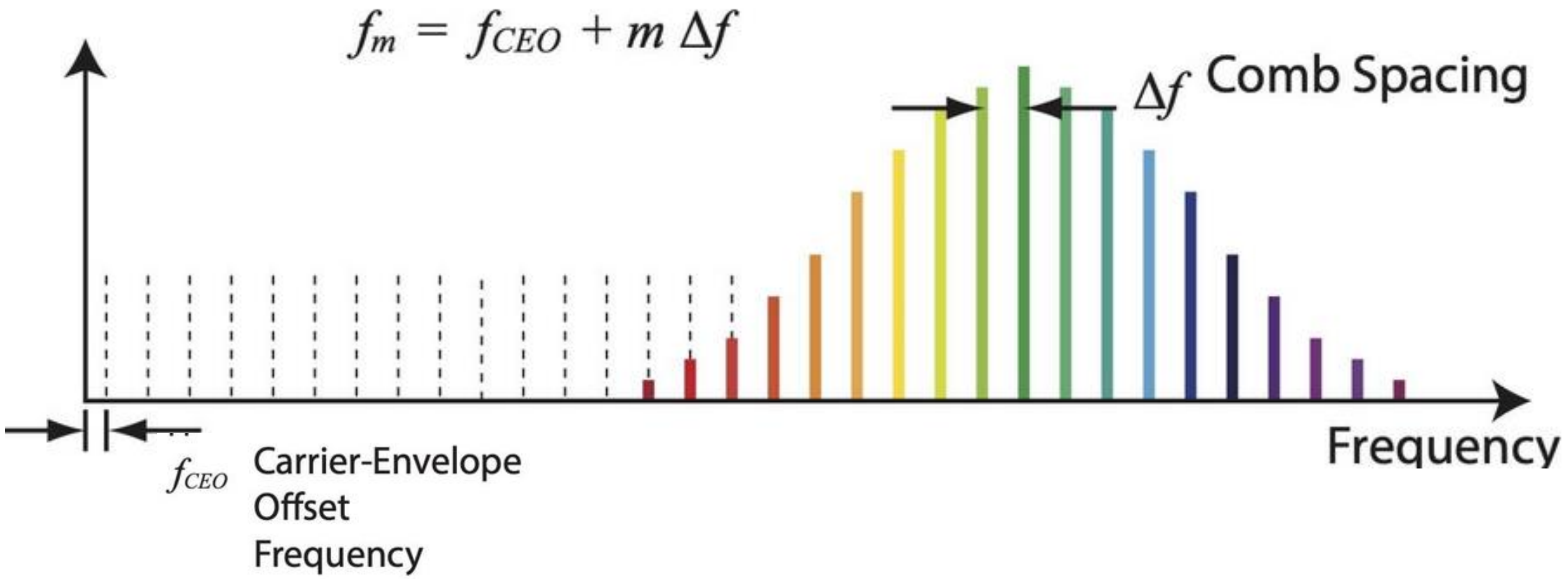


All-fiber femtosecond lasers at 920 nm

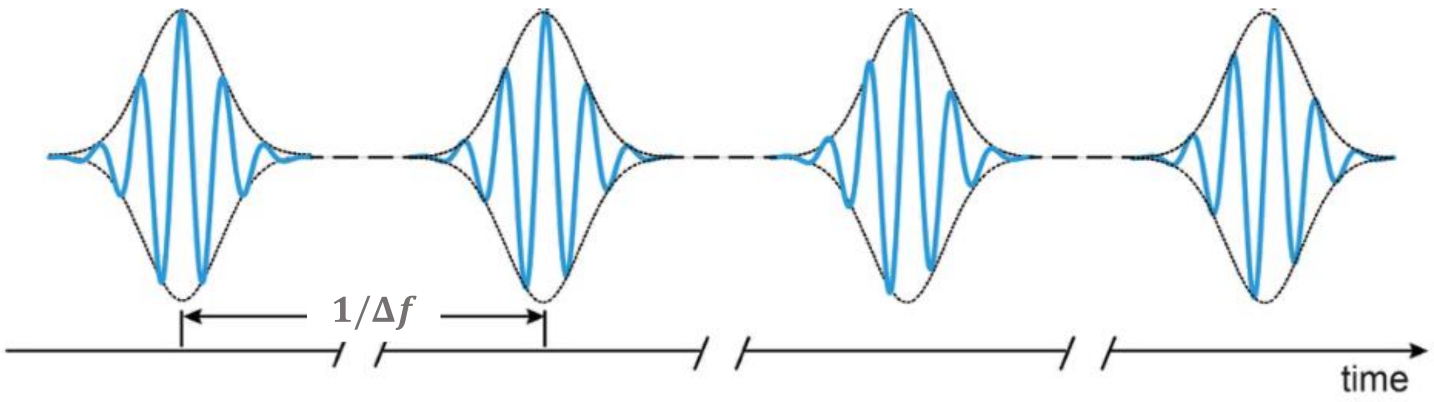


Optical frequency combs

Frequency domain



Time domain

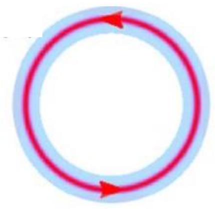


<u>Comb characteristics:</u>

$\Delta f \equiv Free\ Spectral\ Range\ (FSR)$

Repetition rate:

$$T_R = \frac{1}{\Delta f} = \frac{L\, n_{gr}}{c}$$



for the ring cavity

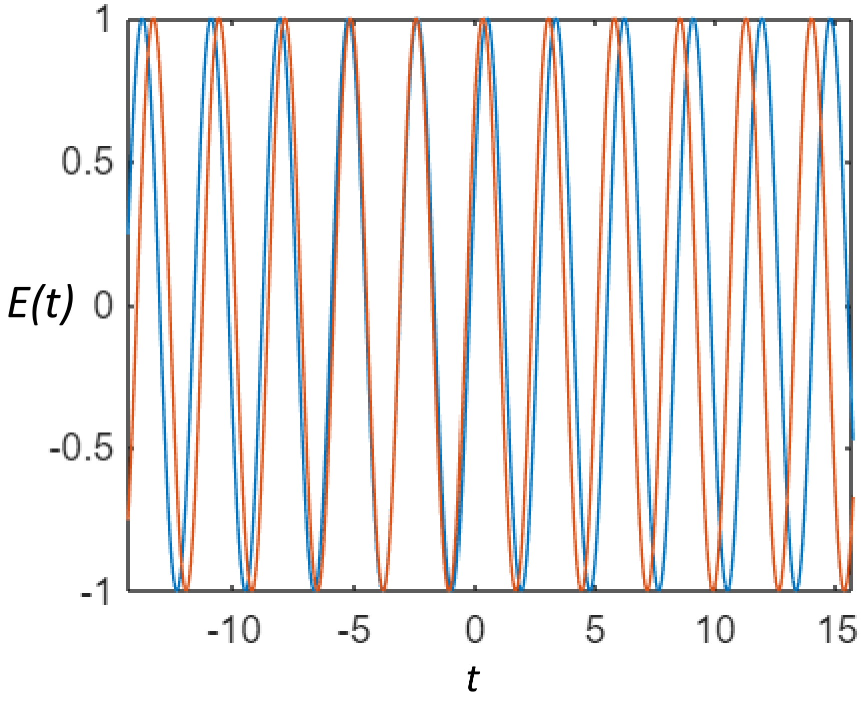
Comb width

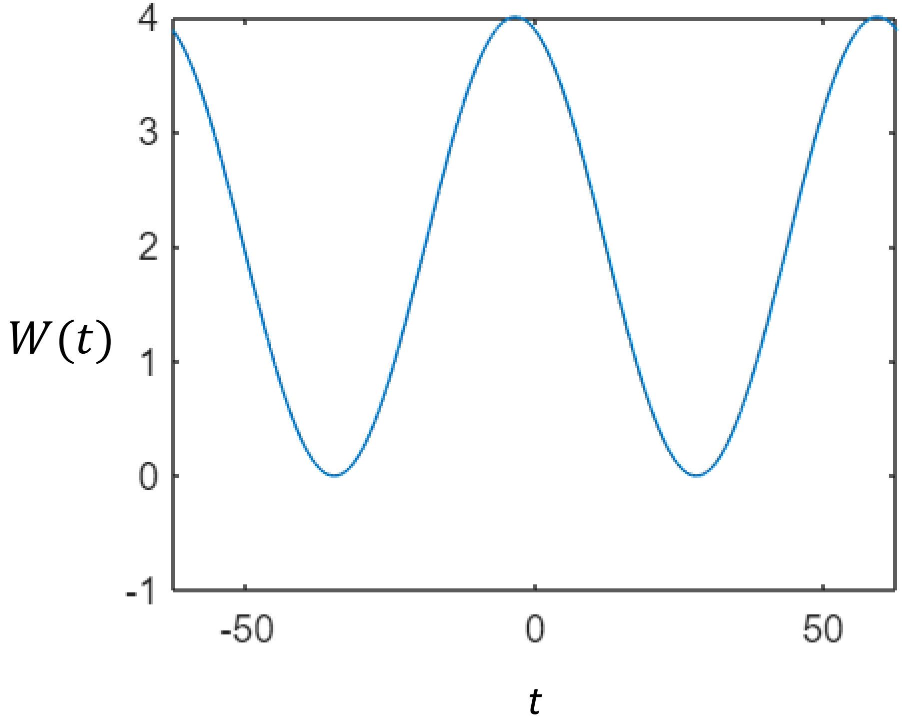
Coherence

Examples of mode summation

2 modes

$$W(t) = \left| \sum_{l=0}^{1} E_0 e^{i(\omega_0 + l\Delta\omega)\, t + i\varphi_l} \right|^2$$





Examples of mode summation

5 modes, random phase

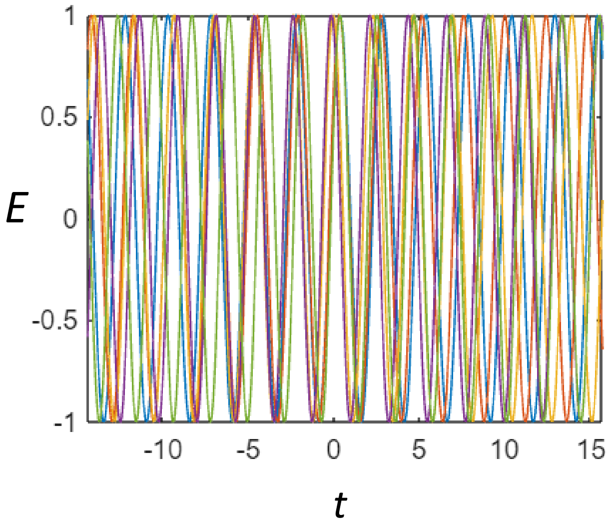
$$W(t) = \left| \sum_{l=0}^{2} E_0 e^{i(\omega_0 + l\Delta\omega)\, t + i\varphi_l} \right|^2$$

5 modes, phase locked

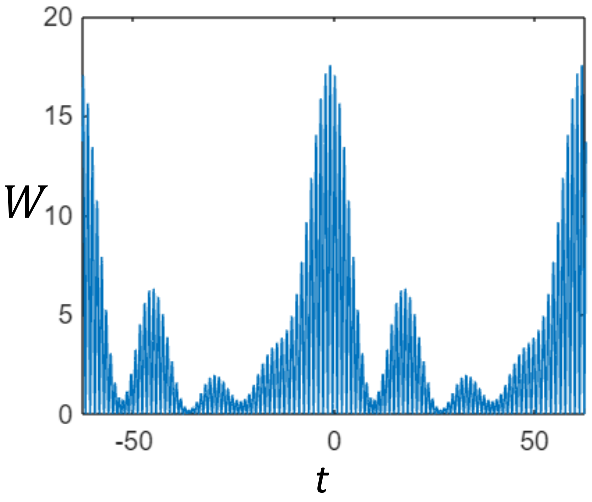
$$W(t) = \left| \sum_{l=0}^{2} E_0 e^{i(\omega_0 + l\Delta\omega)\, t + il\varphi_0} \right|^2$$

$$\varphi_{l+1} - \varphi_l = \varphi_0$$

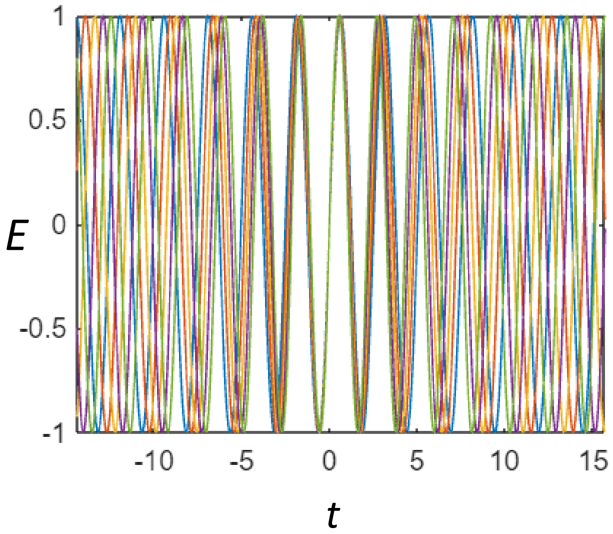
Modes



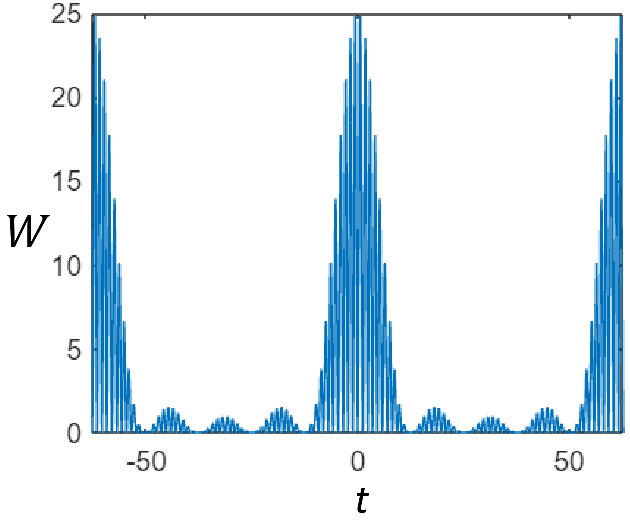
Intensities



Modes



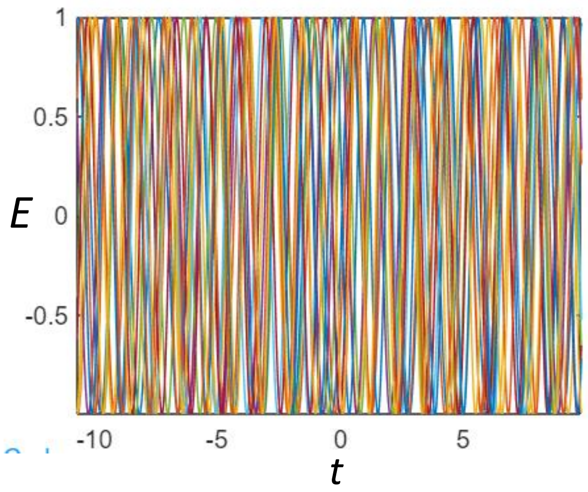
Intensities

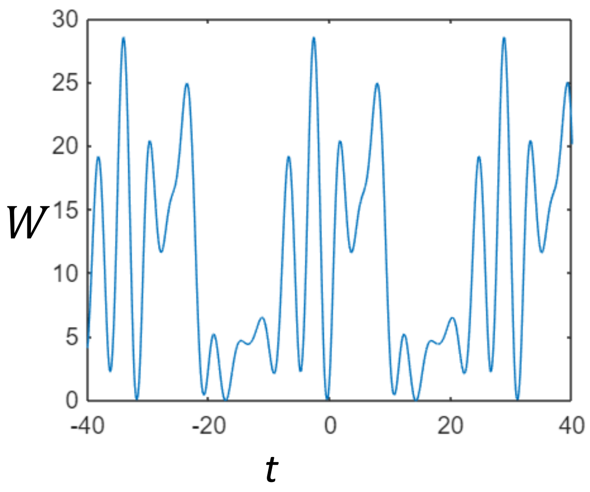


Examples of mode summation

20 modes, random phase

$$W(t) = \left| \sum_{l=0}^{19} E_0 e^{i(\omega_0 + l\Delta\omega)\, t + i\varphi_l} \right|^2$$

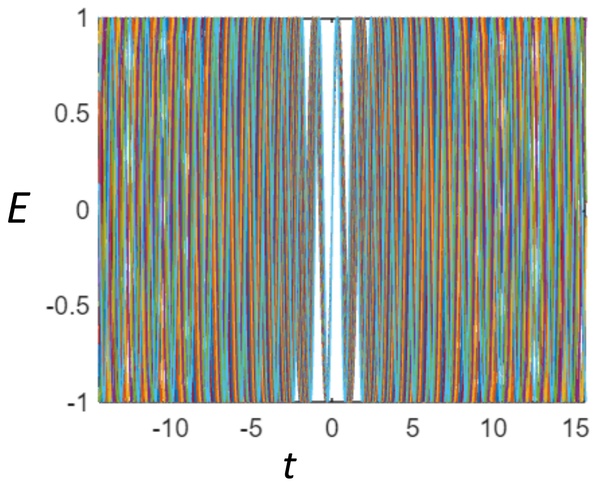


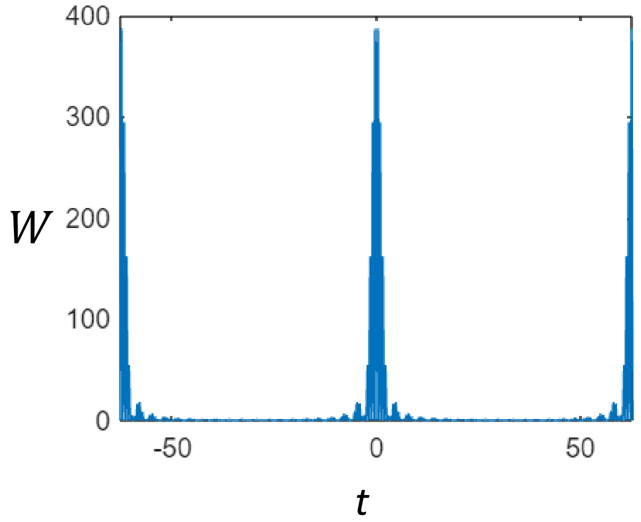


20 modes, phase locked

$$W(t) = \left| \sum_{l=0}^{19} E_0 e^{i(\omega_0 + l\Delta\omega)\, t + il\varphi_0} \right|^2$$

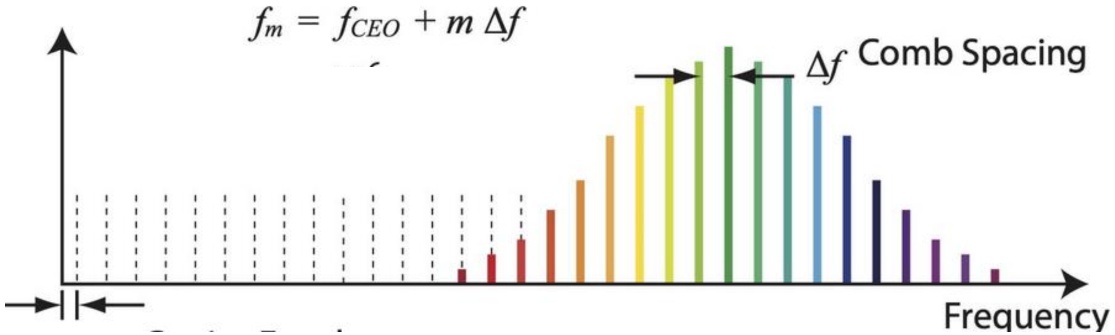
$$\varphi_{l+1} - \varphi_l = \varphi_0$$



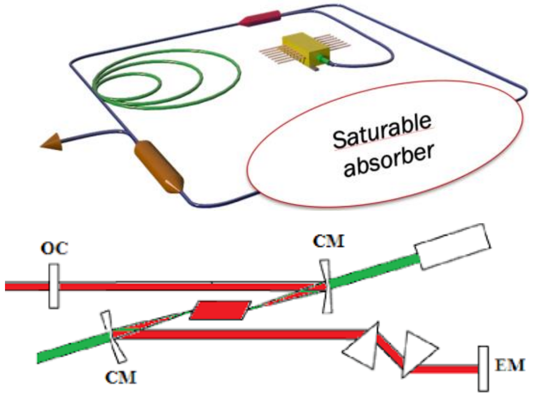


Optical frequency combs

Frequency domain

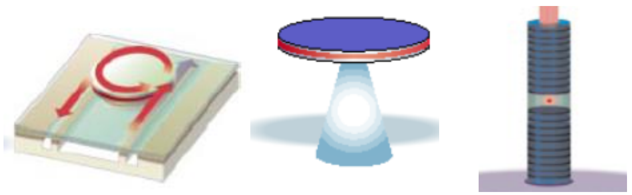


Mode-locked lasers



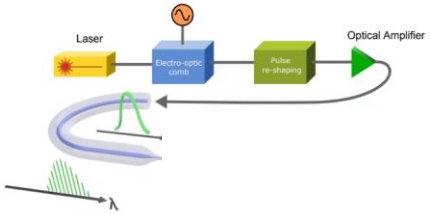
FSR=10 to 100 MHz

High-Q microcavities

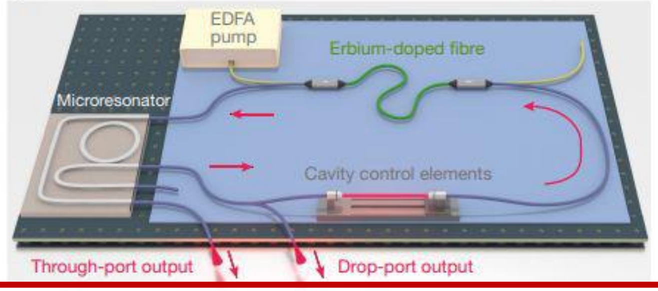


FSR=10 to 1000 GHz

Electro-optic comb generators

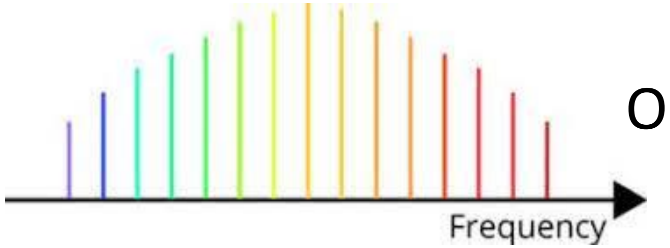


FSR up to 50 GHz

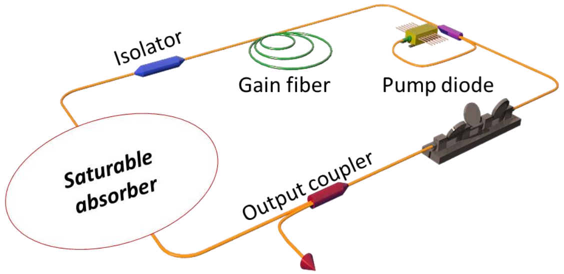


Laser with integrated high-Q microcavity

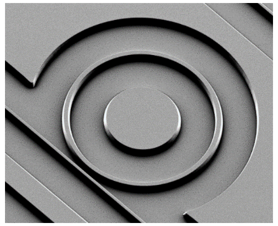
Content



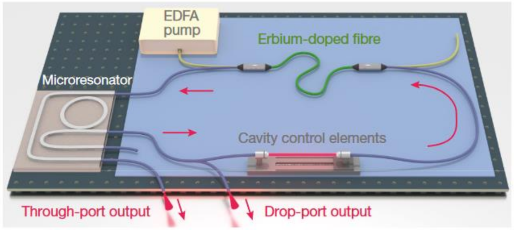
Optical frequency combs



Ultrafast fiber lasers

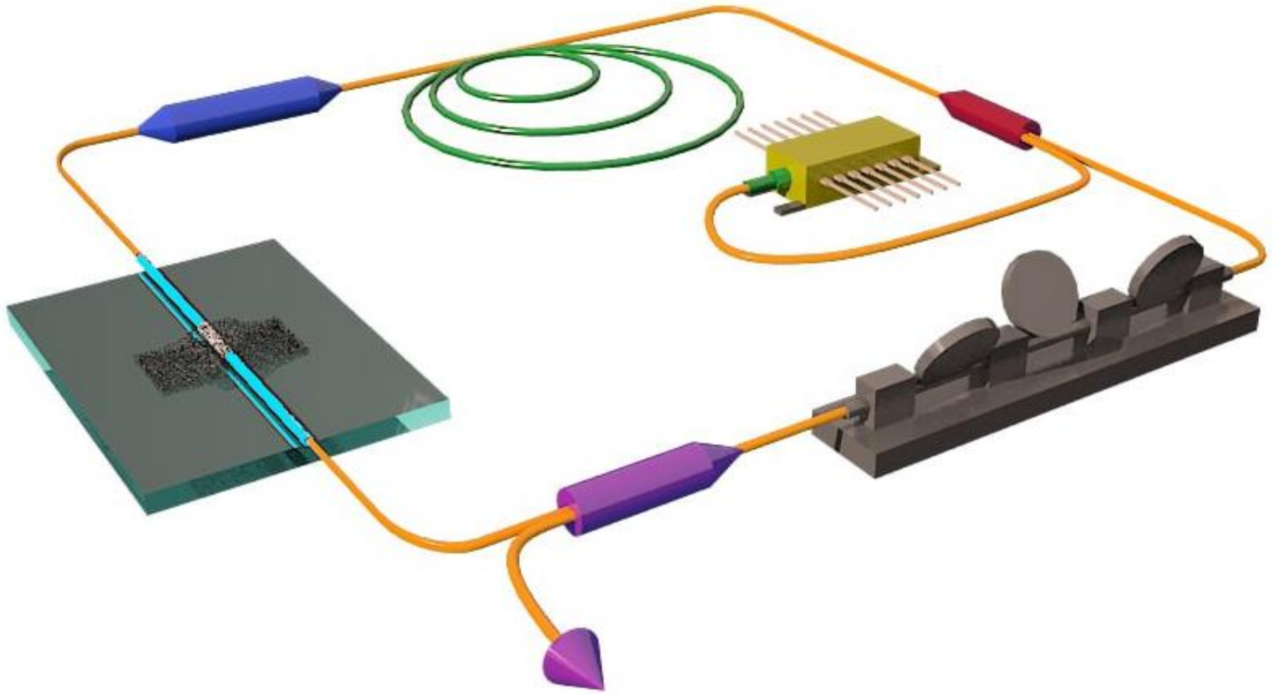


Microcavity combs



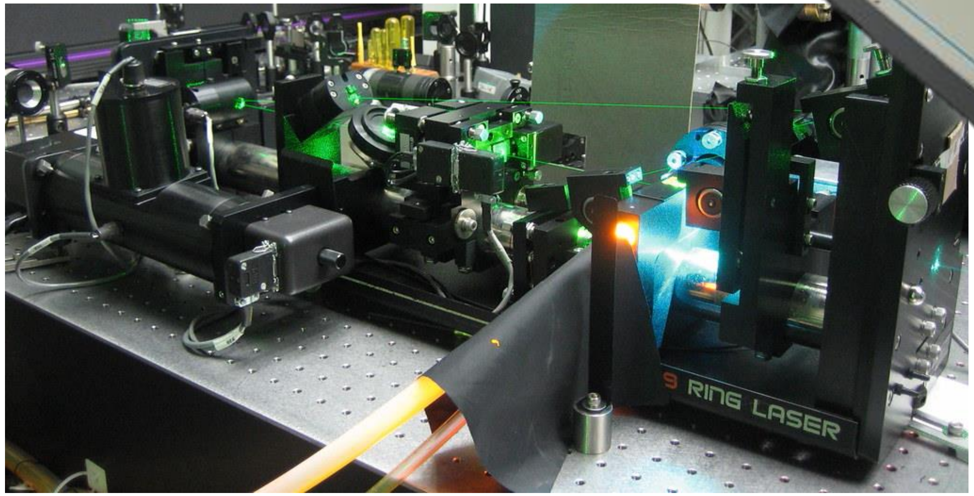
Laser microcavity combs

Ultrafast fiber lasers



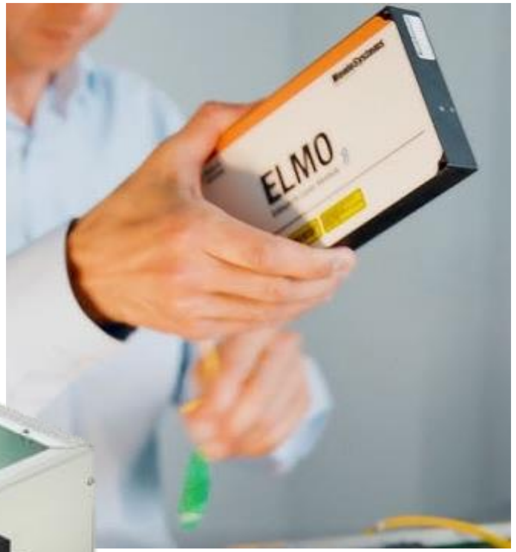
Mode-locked femtosecond lasers

Dye lasers (1972)



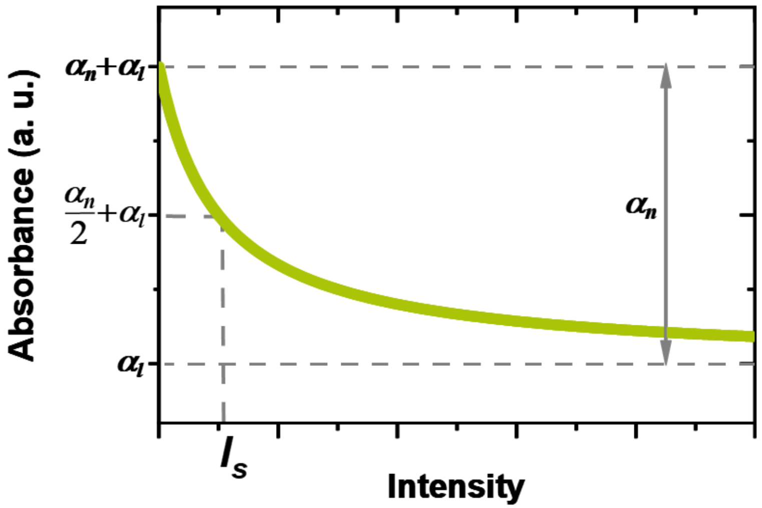
Ti:Sa lasers (1980x)

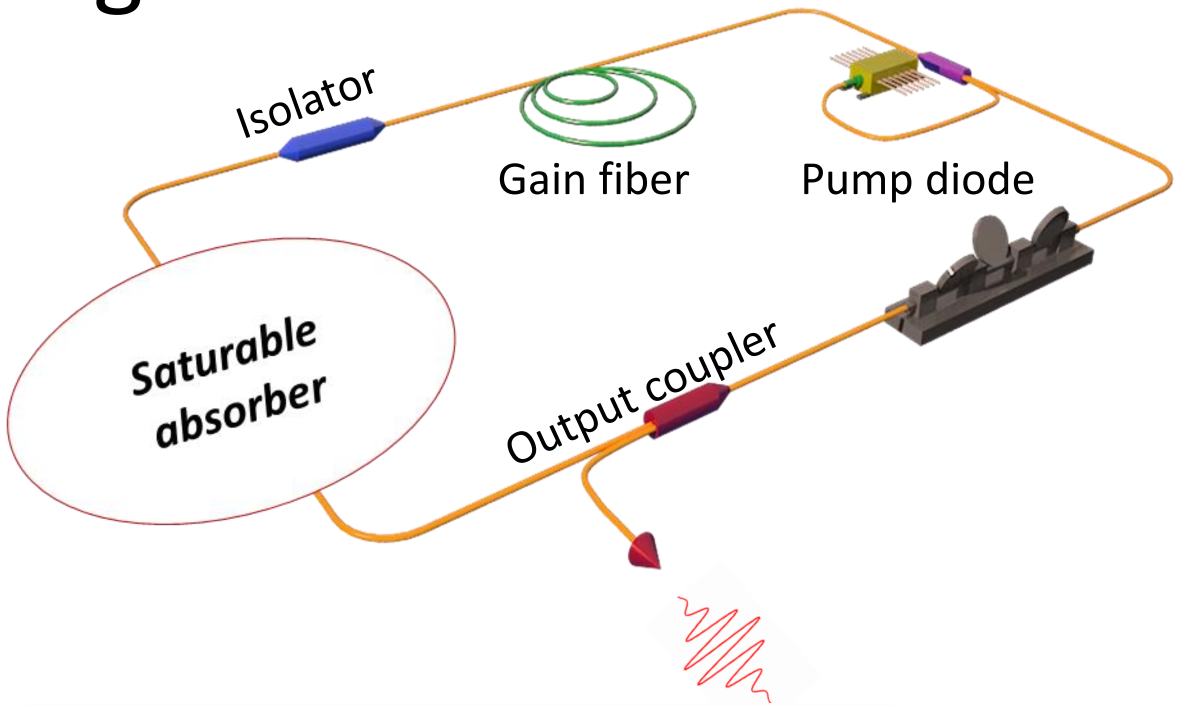
Fiber lasers



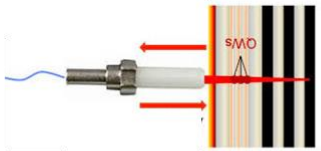
Semiconductor lasers

Fiber laser mode locking mechanism

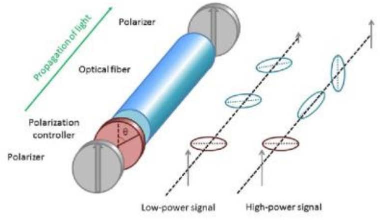


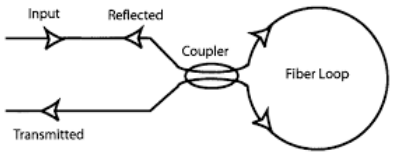


Material SA

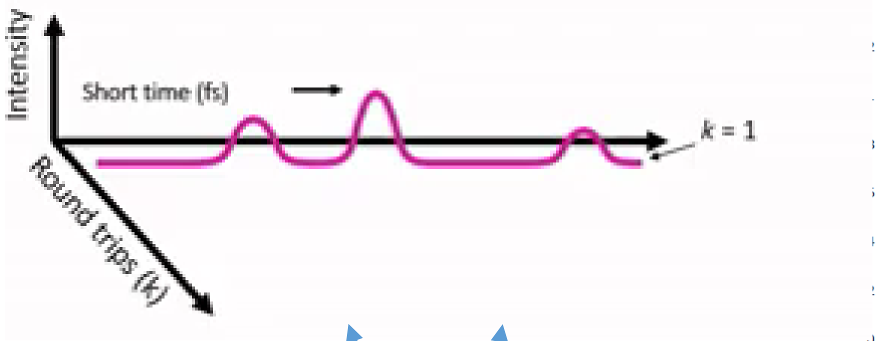


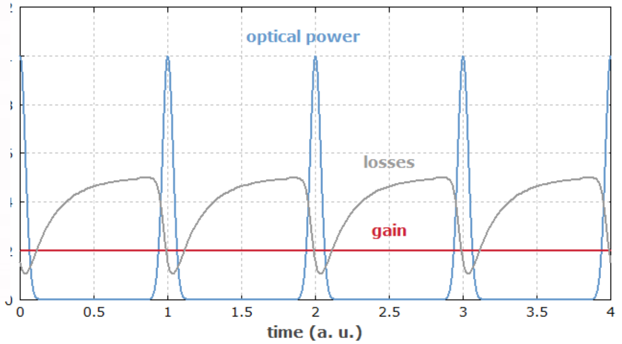
Artificial SA





Schematic of an all-fiber Sagnac interferometer acting as a nonlinear optical loop mirror whose transmission depends on launched input power.



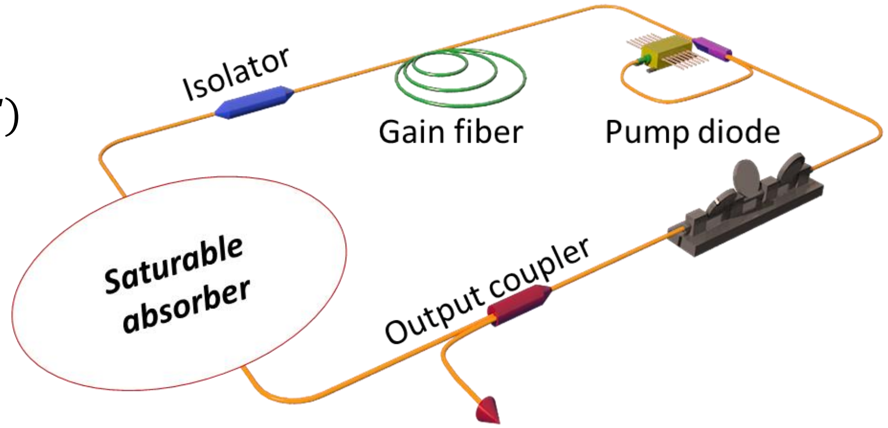


Weak pulses suppressed, strong pulse shortens and amplified

Fiber mode locked lasers

$$\frac{\partial E(z,T)}{\partial z} - \frac{1}{v_g}\frac{\partial E(z,T)}{\partial t} = [g + D_g \frac{\partial^2}{\partial t^2} - l_0 - \frac{\kappa}{1+|E|^2/I_{sat}} + iD_2\frac{\partial^2}{\partial t^2} - i\gamma_K |E|^2]E(z,T)$$

Pulse propagation — *gain + spectral filter* — *losses* — *saturable absorber* — *Dispersion* — *Nonlinearity*

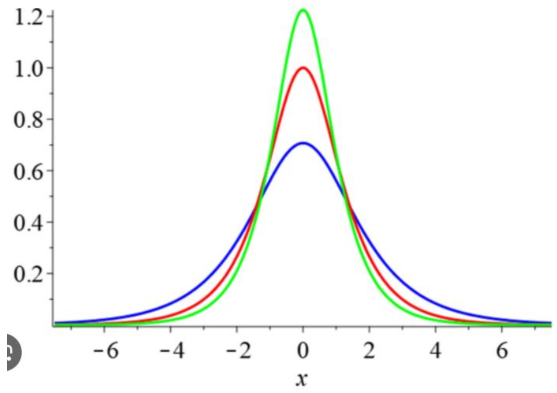


Soliton solution (anomalous dispersion):

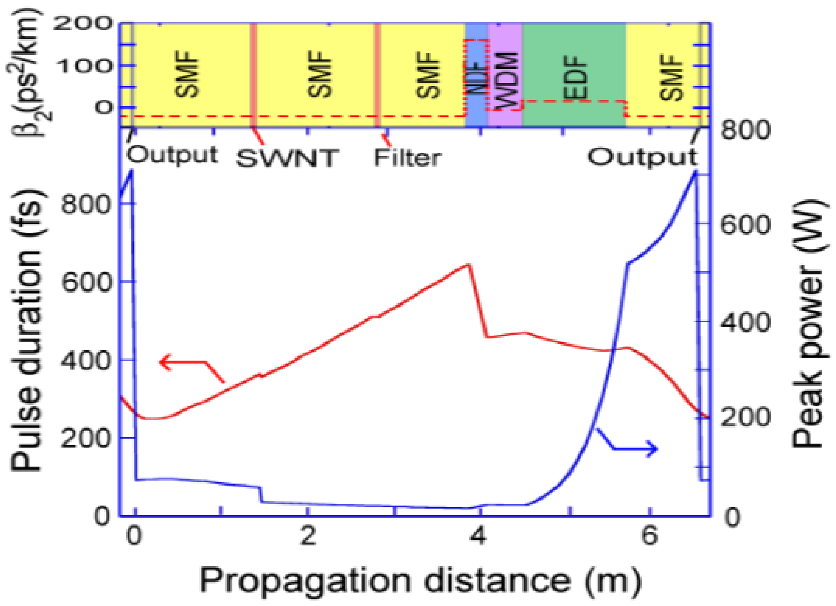
$$E = \eta \, \mathrm{sech}\big((t - z/v_g)\eta/\tau_p\big)\, e^{i\eta^2 z/L_D}$$

Soliton area theorem:

$$W_{pulse} = \frac{|D_2|}{\gamma_k \tau_p} = \frac{3.11|D_2|}{\gamma_k \tau_{FWHM}}$$



In **real laser** soliton parameters are constantly changing

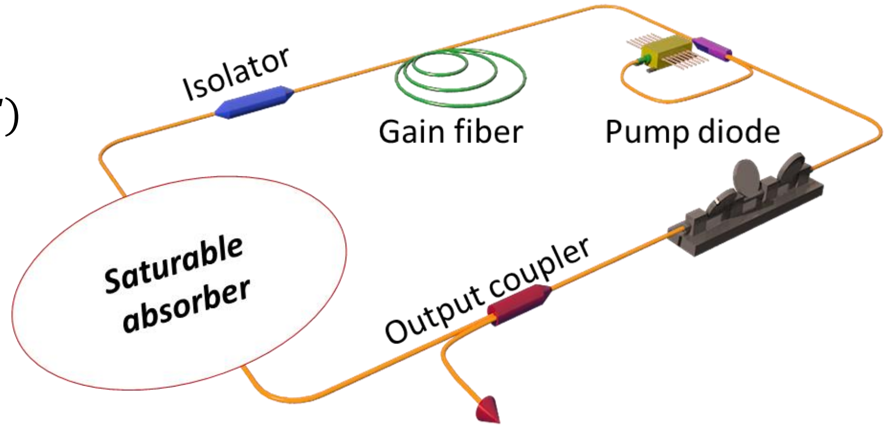


N. Nishizawa et al, Photonics 2(3):808-824, 2015

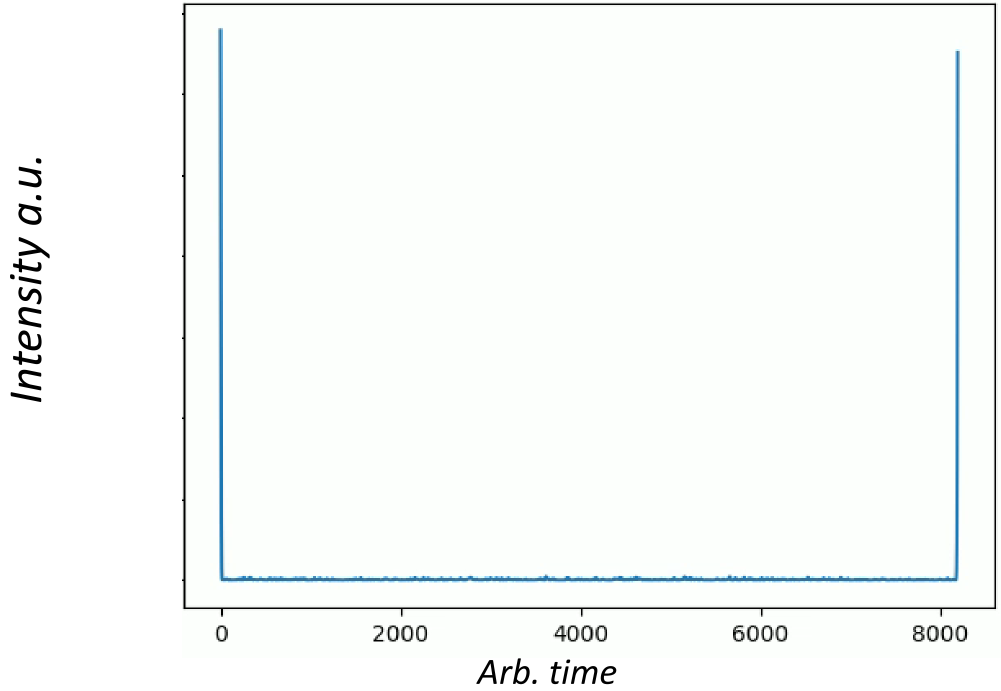
Fiber mode locked lasers

$$\frac{\partial E(z,T)}{\partial z} - \frac{1}{v_g}\frac{\partial E(z,T)}{\partial t} = [g + D_g\frac{\partial^2}{\partial t^2} - l_0 - \frac{\kappa}{1+|E|^2/I_{sat}} + iD_2\frac{\partial^2}{\partial t^2} - i\gamma_K|E|^2]E(z,T)$$

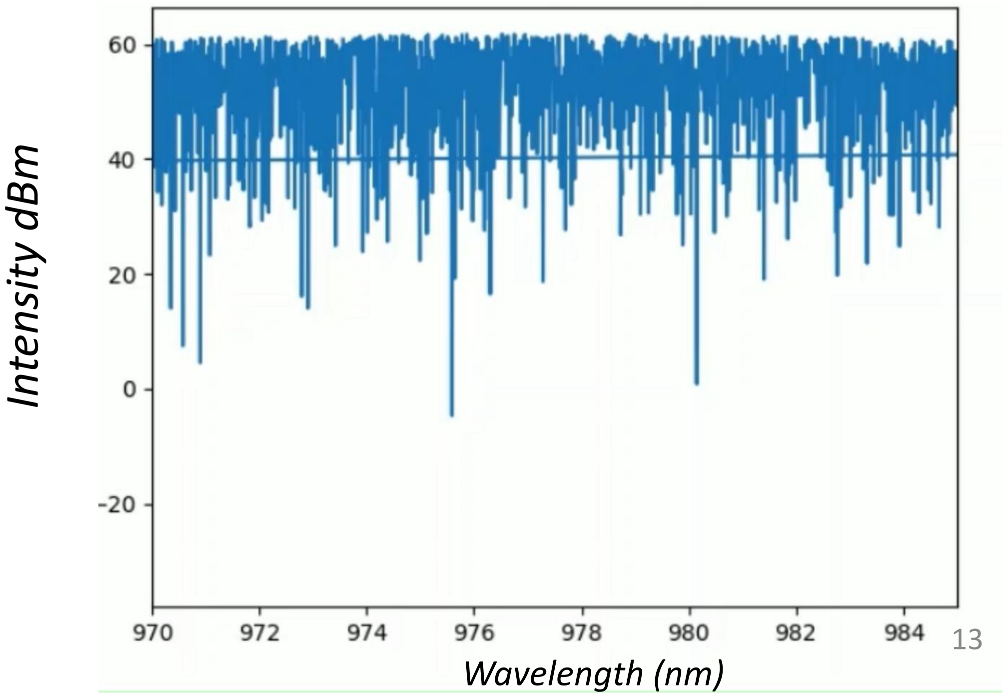
Pulse propagation · *gain + spectral filter* · *losses* · *saturable absorber* · *Dispersion* · *Nonlinearity*



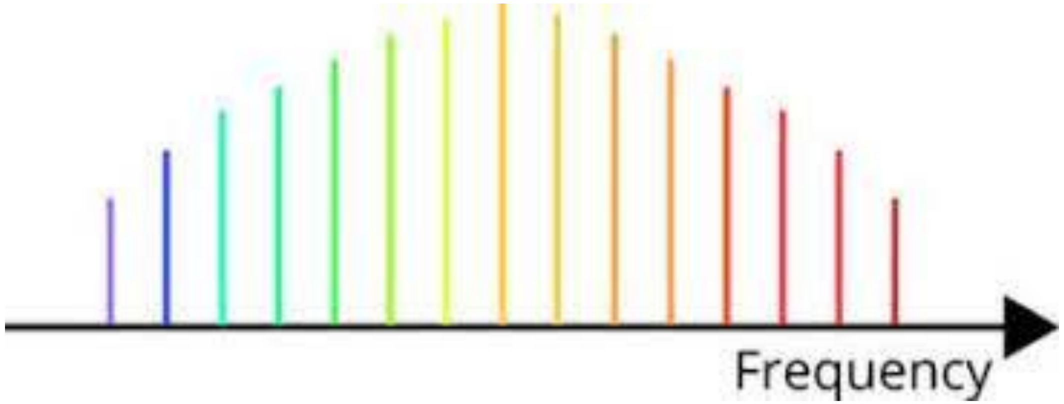
Numerical simulation (time domain)

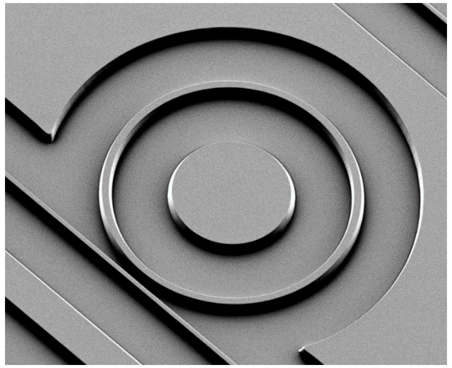


Numerical simulation (spectrum)



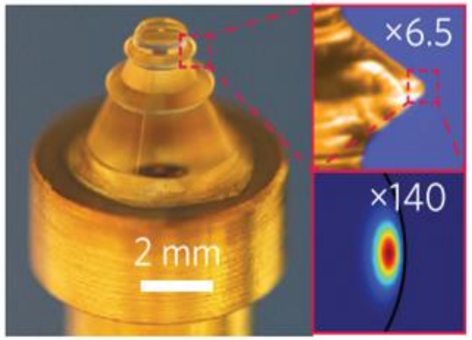
Microcavity frequency combs

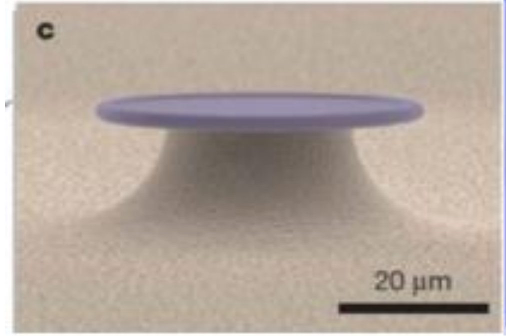


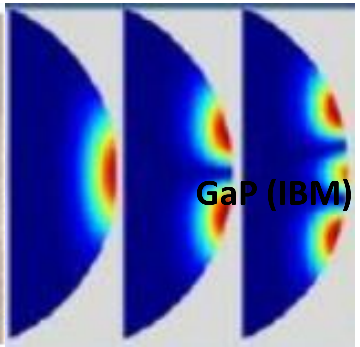


Platforms for soliton microcomb generation

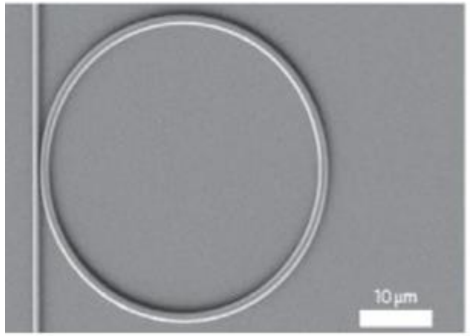
Whispering gallery mode cavities

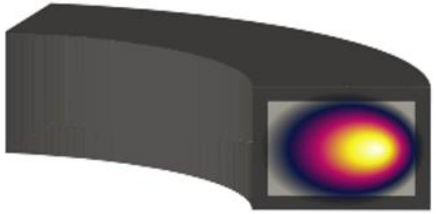






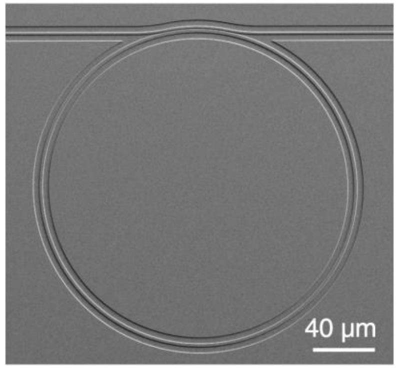
Integrated microrings



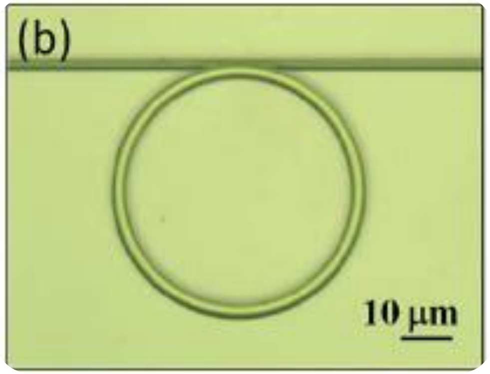


Microring platforms

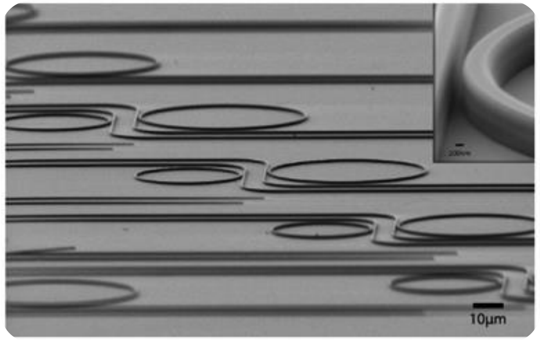
$LiNbO_3$ (Rochester, Caltech)



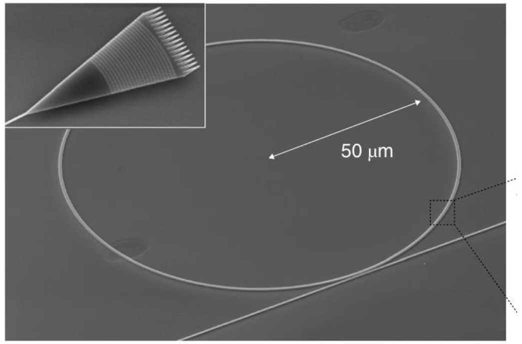
AlN (Yale), AlGaAs (NIST)



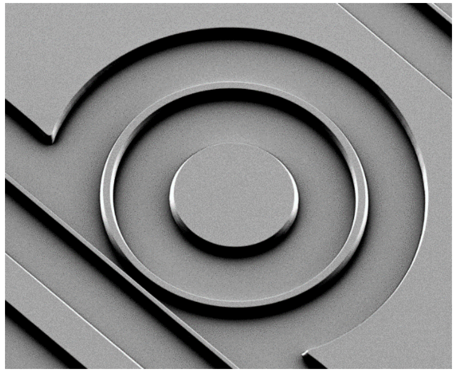
Diamond (Harvard)



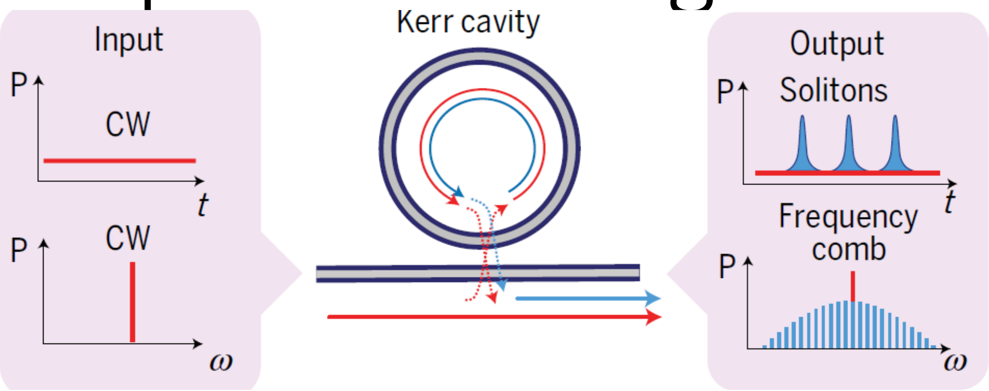
GaP (IBM)

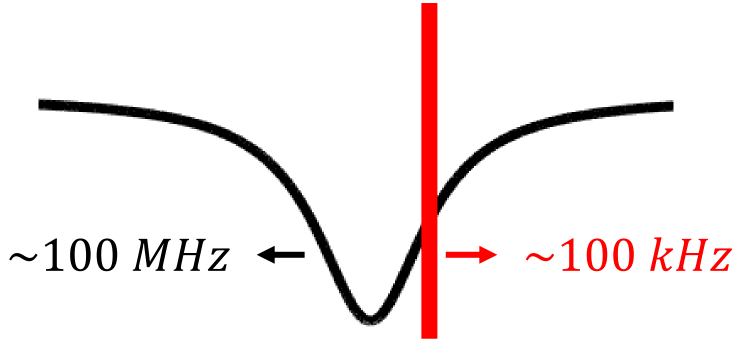


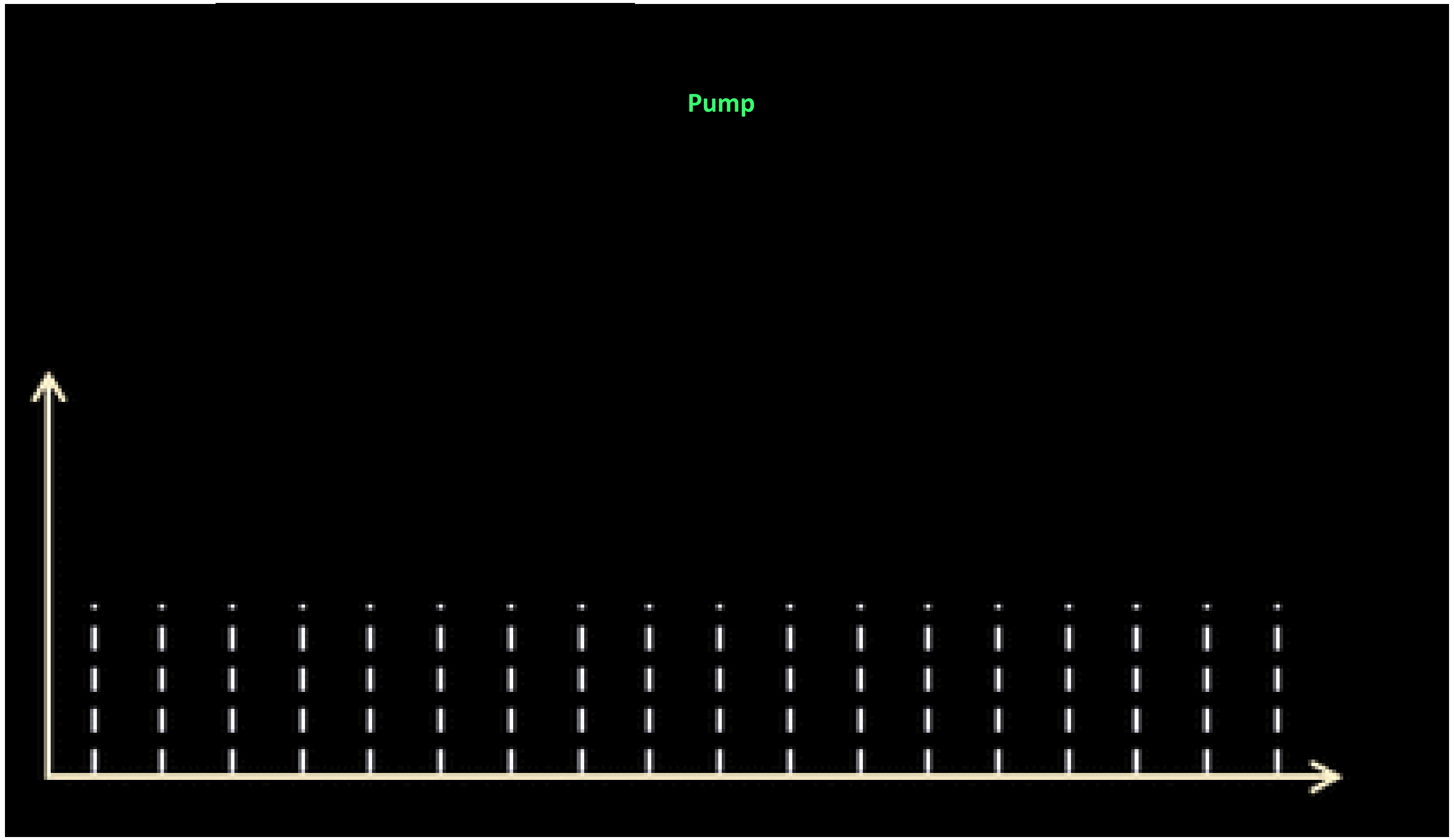
Silicon Nitride (Columbia, UCSB, EPFL)



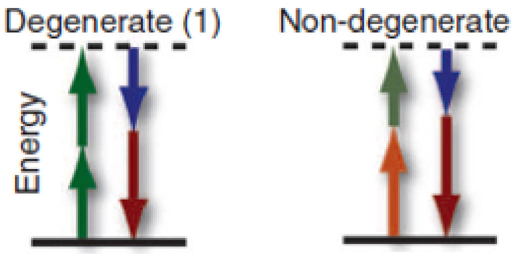
Principle of comb generation







Energy is transferred from initial mode to neighboring mode by four wave mixing mechanism

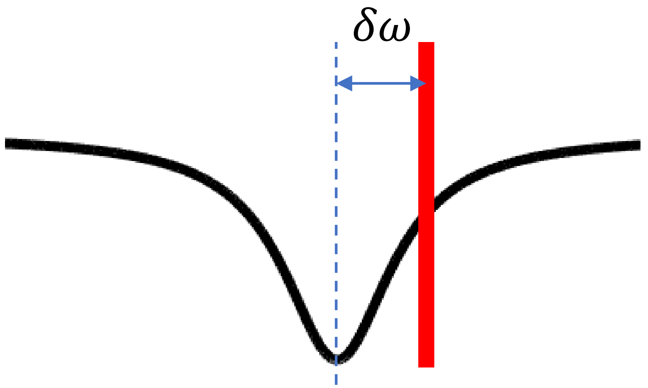


LLE equation

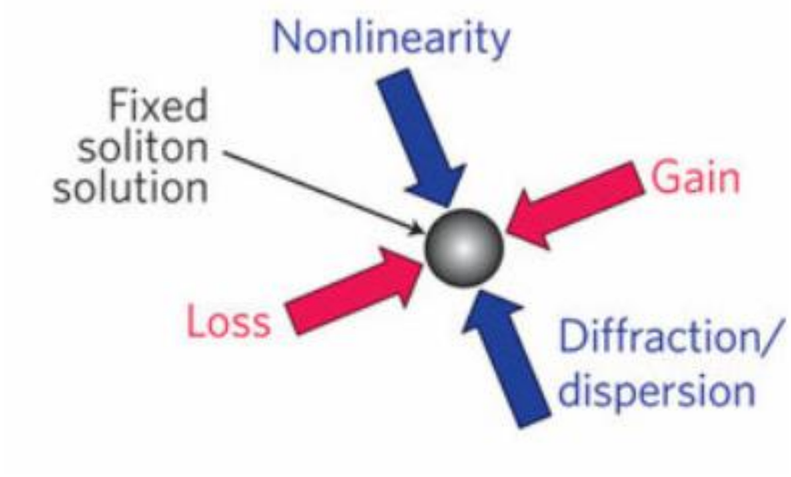
Lugiato-Lefever equation (LLE)

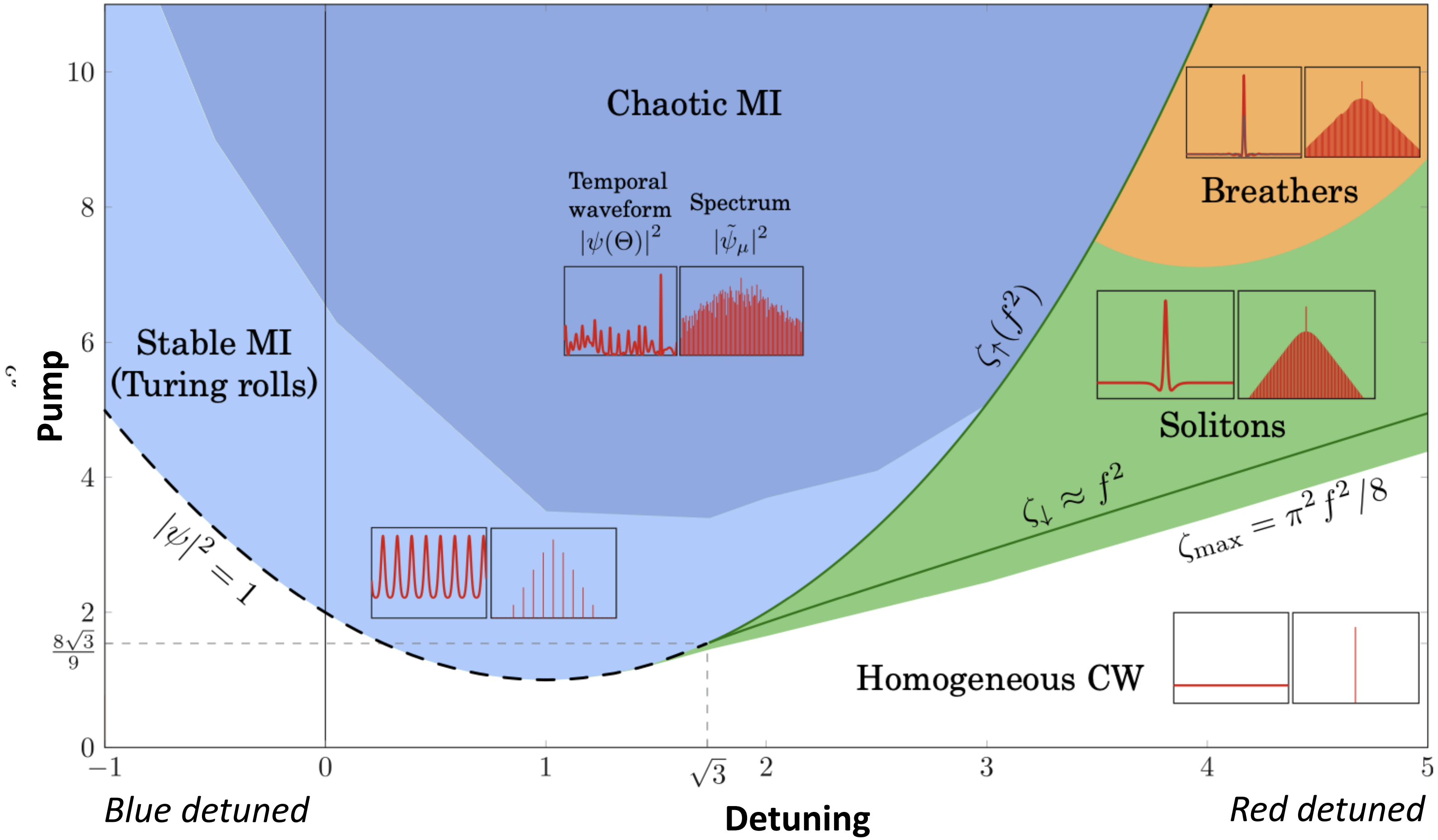
$$\frac{\partial A}{\partial t} = \left(-\left(\frac{\kappa}{2} + i\delta\omega\right) + i\frac{D_2}{2}\frac{\partial^2}{\partial\phi^2} + i g_0 |A|^2\right) A + \sqrt{\kappa_{\mathrm{ex}}}\, s_{\mathrm{in}}$$

Loss   Detuning   Dispersion   Nonlinearity   Pump



Temporal cavity soliton – a localized structure emerging as interplay of nonlinearity and dispersion on one side and losses and pump on the other.





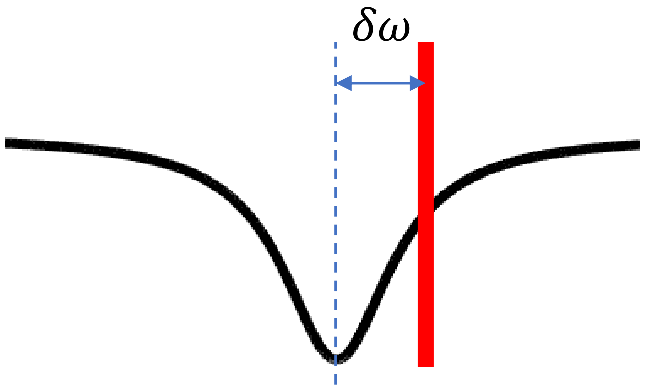
Phys. Rev. A 89, 063814

LLE equation

Lugiato-Lefever equation (LLE)

$$\frac{\partial A}{\partial t} = \left(-\left(\frac{\kappa}{2} + i\delta\omega \right) + i\frac{D_2}{2}\frac{\partial^2}{\partial \phi^2} + i g_0 |A|^2 \right) A + \sqrt{\kappa_{ex}}\, s_{in}$$

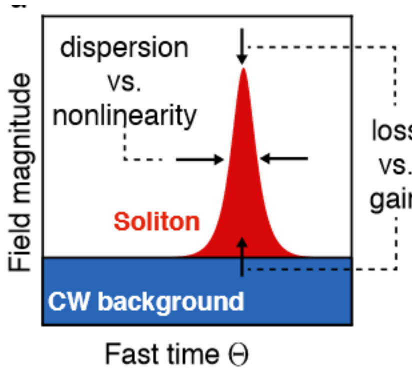
Loss Detuning Dispersion Nonlinearity Pump



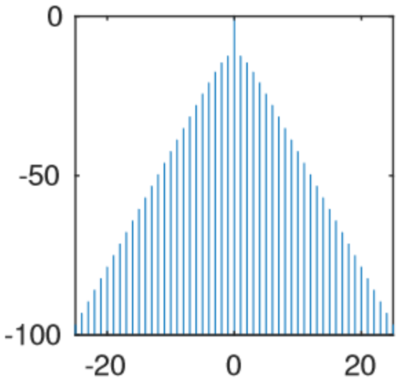
Exact soliton solution is not known

Approximate solution of NLSE (cavity solitons):

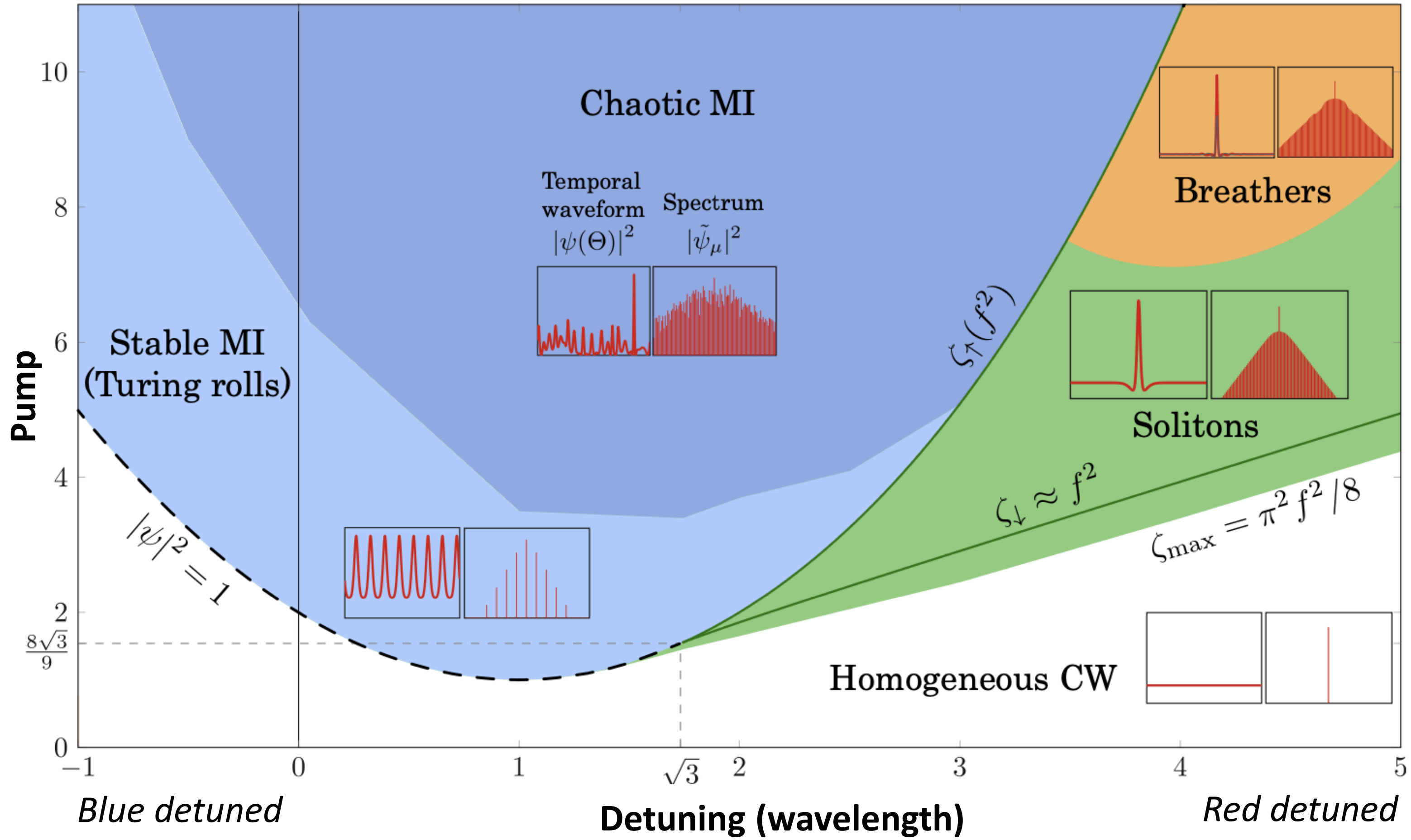
$$A(t,\tau) = \sqrt{\frac{2\delta\omega}{g_0}}\,\mathrm{sech}\left(\frac{\tau}{\Delta\tau_s}\right)$$



Profile



Spectra



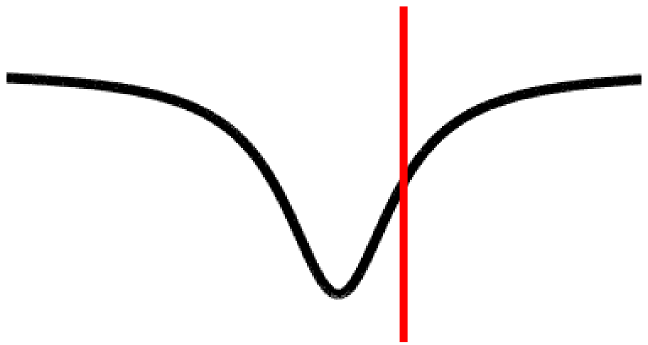
Phys. Rev. A 89, 063814

Real life

Lugiato-Lefever equation (LLE)

$$\frac{\partial A}{\partial t} = \left(-\left(\frac{\kappa}{2} + i\delta\omega\right) + i\frac{D_2}{2}\frac{\partial^2}{\partial\phi^2} + i g_0 |A|^2\right) A + \sqrt{\kappa_{ex}}\, s_{in}$$

Loss Detuning Dispersion Nonlinearity Pump

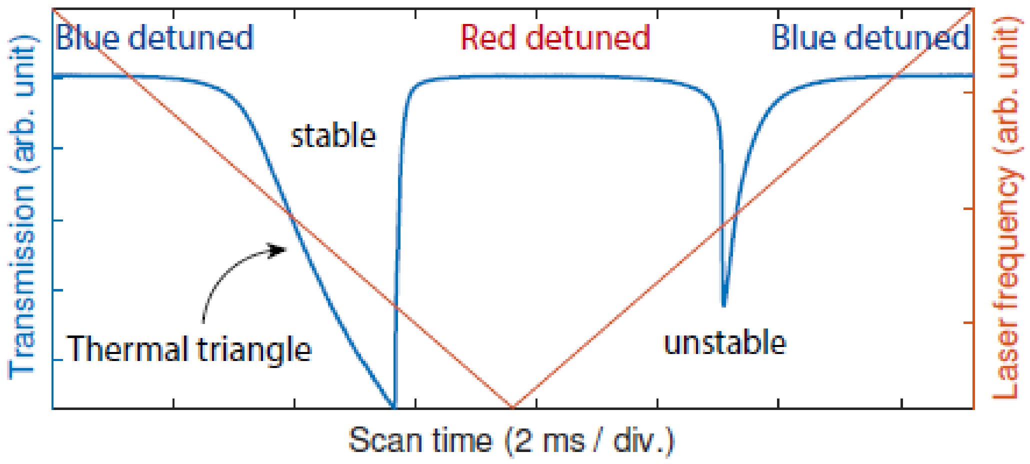


Laser on

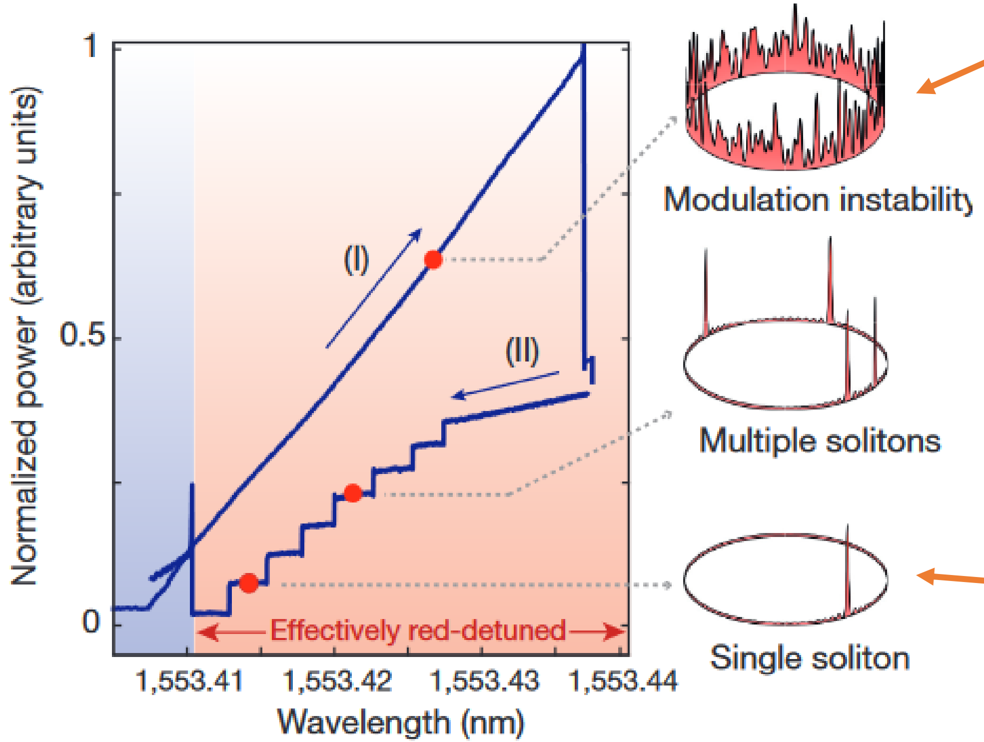
Once you tune the laser to the resonance, it shifts:

Instant shift due to self phase modulation ($n = n_0 + g_0|A|^2$)

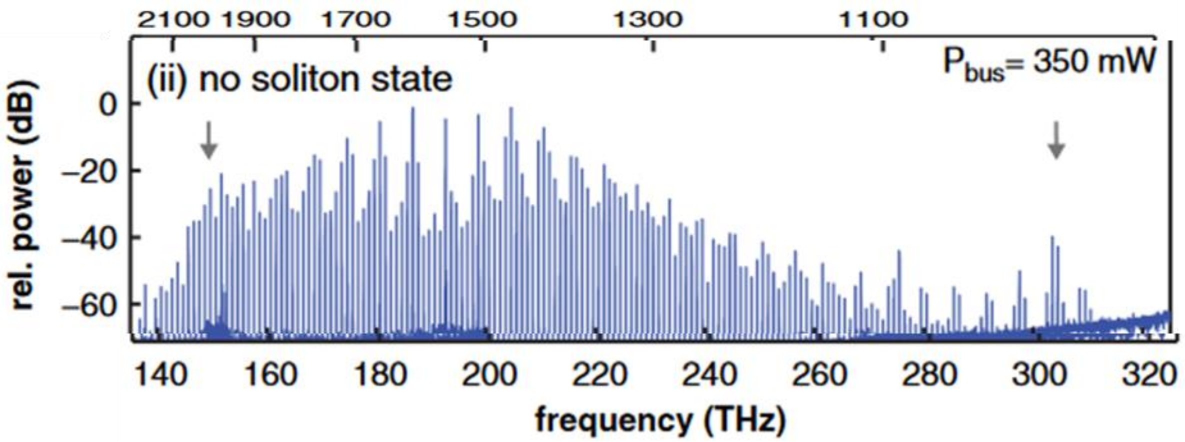
Slow (tens of ns) due to thermal heating ($n = n(T)$)



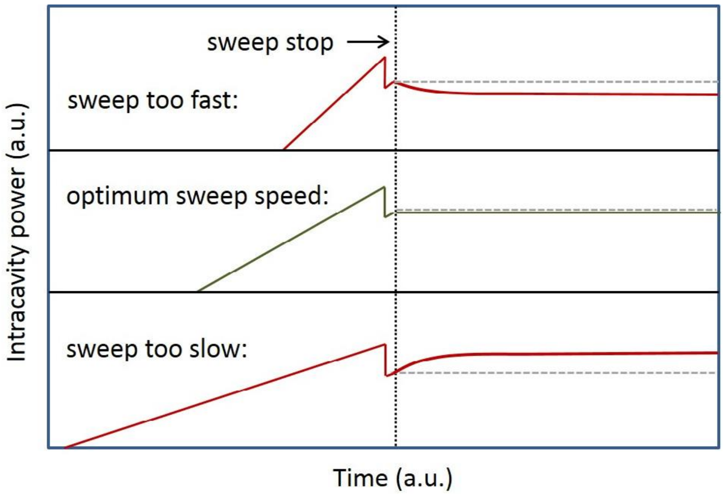
Real life

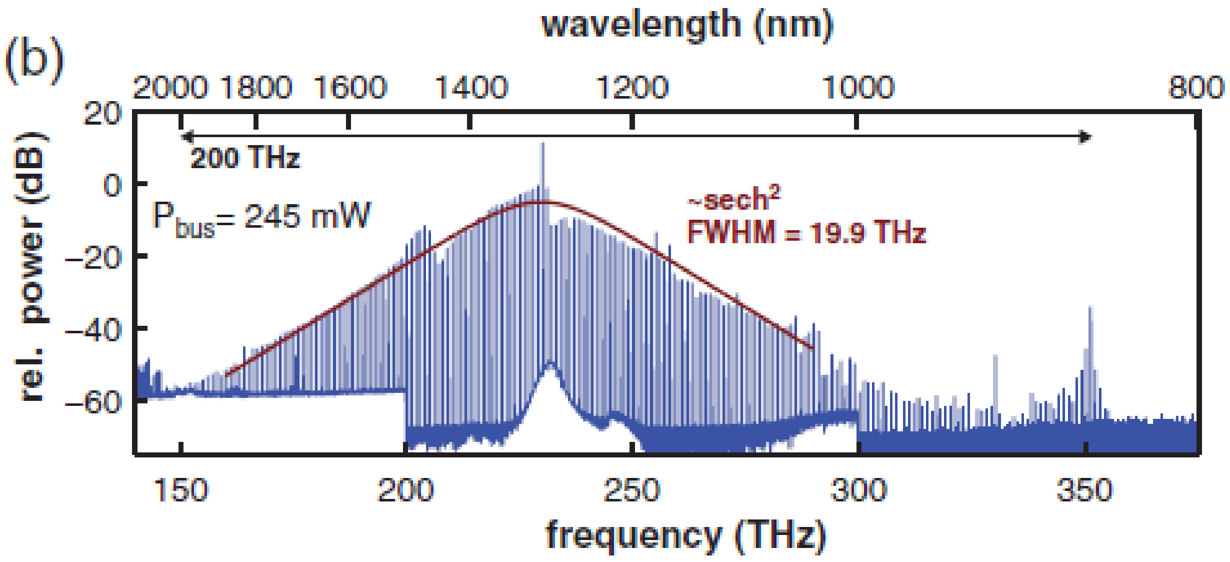


Chaotic regime



Soliton step

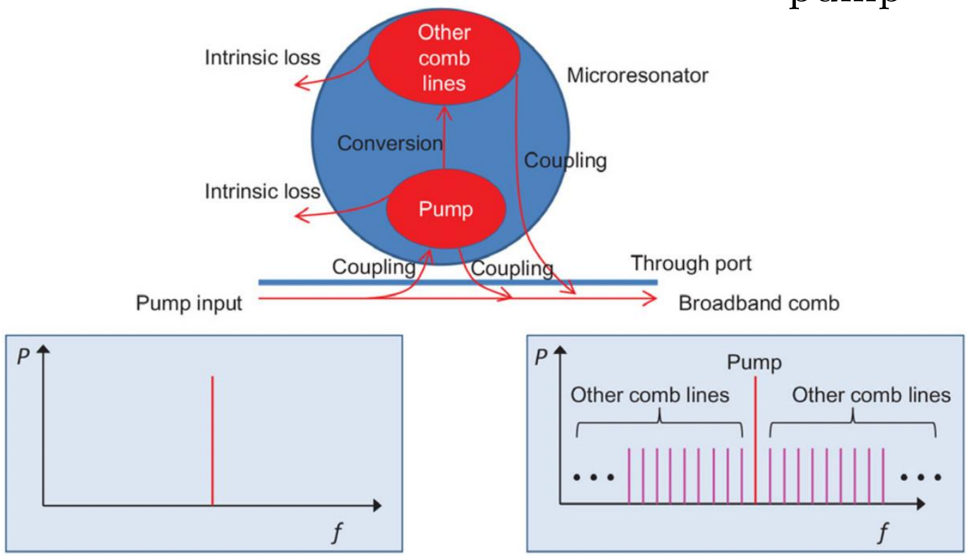




Limitations

- **Low conversion efficiency**

$$\eta = \frac{\mathrm{P}^{\mathrm{out}}_{\mathrm{comb}}}{\mathrm{P}^{\mathrm{in}}_{\mathrm{pump}}}$$



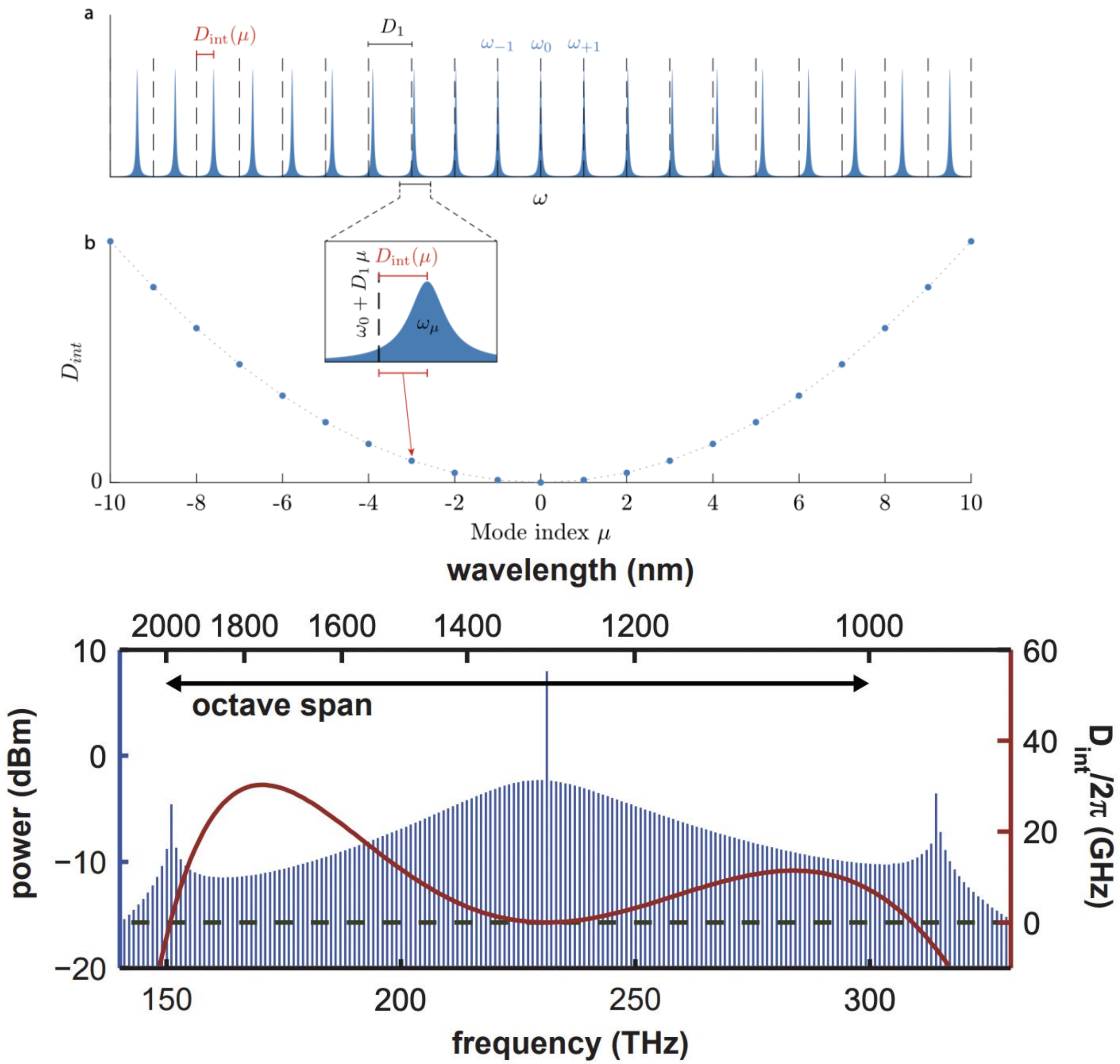
(1 - 4% for single-soliton state microcombs)

⇓

Low output power (<<1 mW)

Xiaoxiao X. et al . Laser Photonics rev, 2017

- **Wide combs requires precise dispersion engineering**

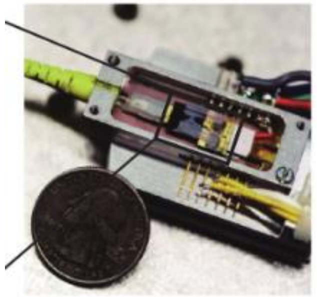


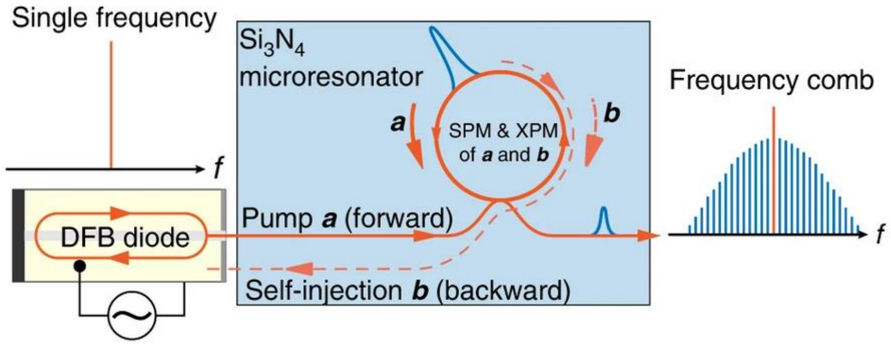
Octave spanning is accessible only for FSR around 1THz

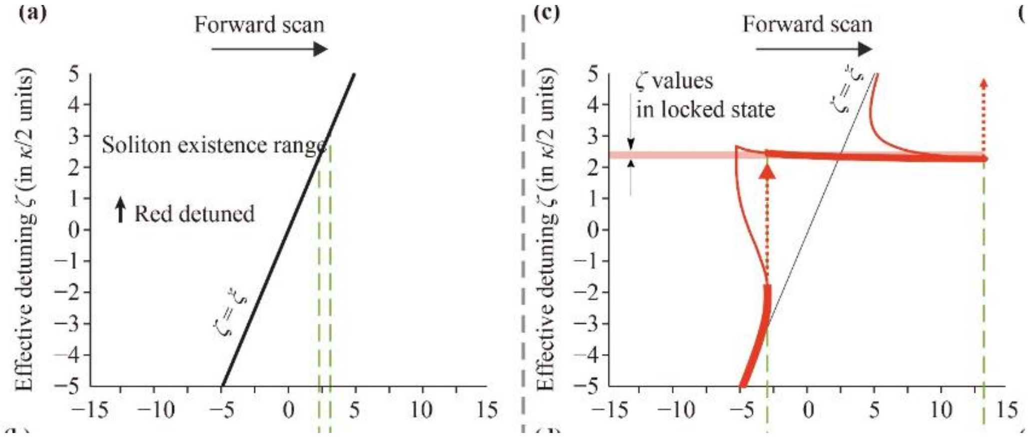
M. Pfeiffer et al, Optica **4**, 684-691 (2017)

Overcoming limitations

Self-injection locking

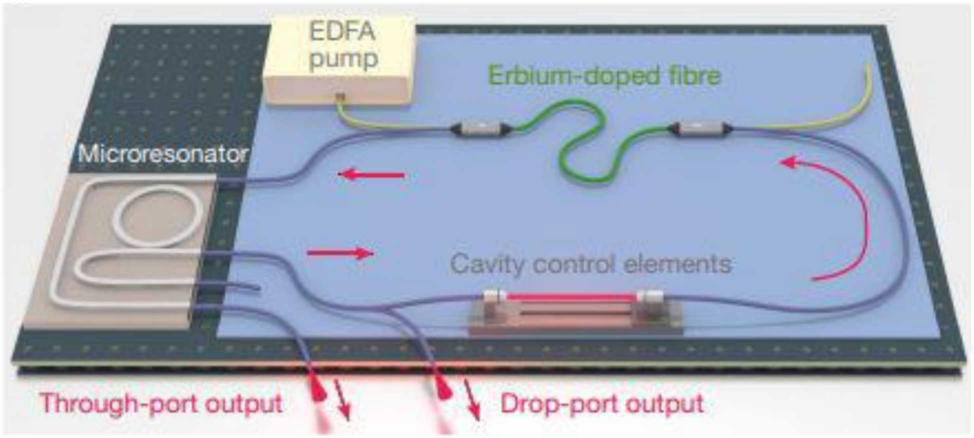


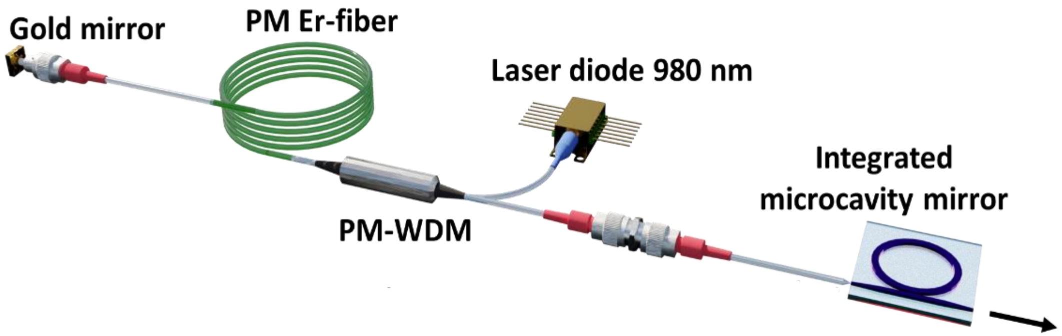




Kondratiev, Front. Phys. 18, 21305 (2023)

Filter driven four wave mixing





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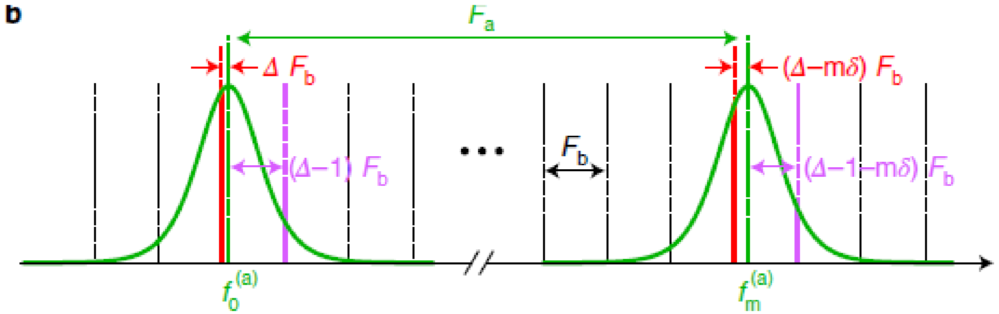
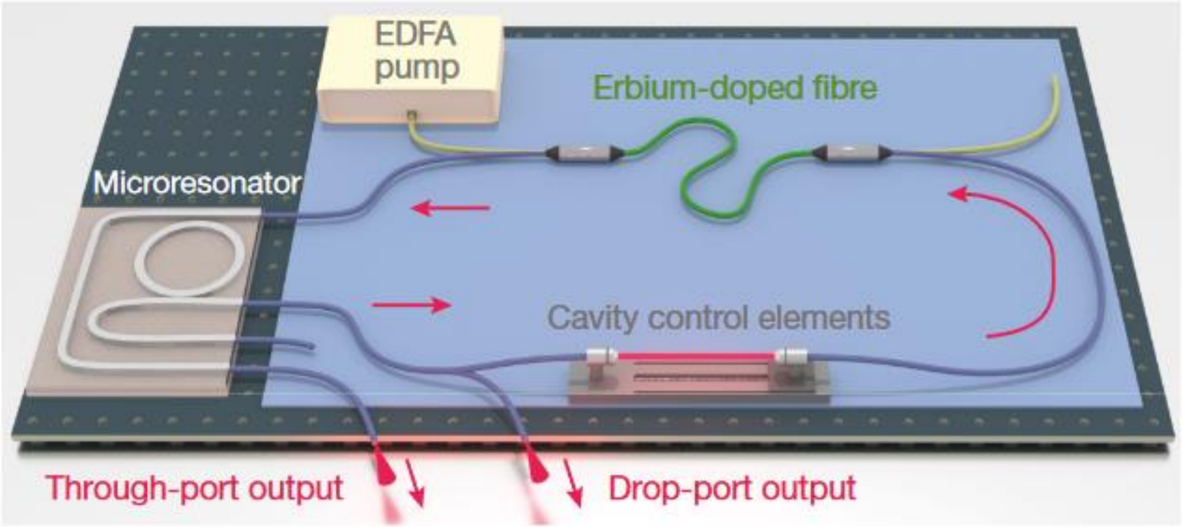
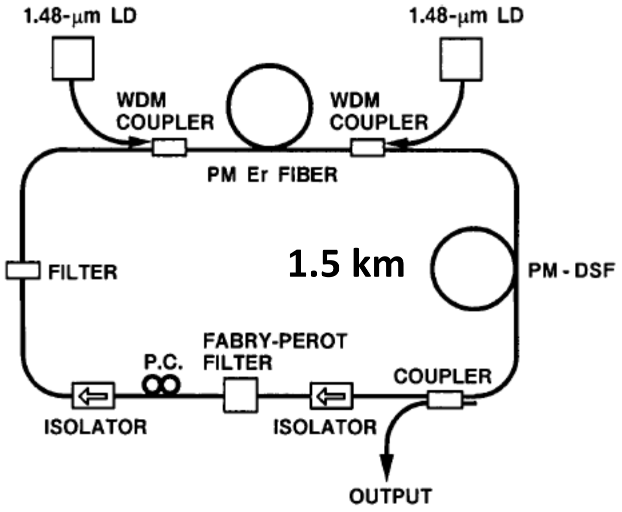




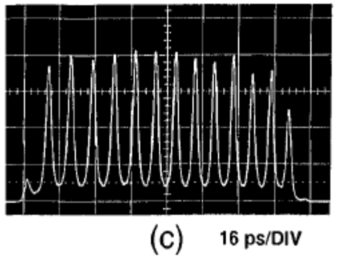
Dissipative four-wave mixing

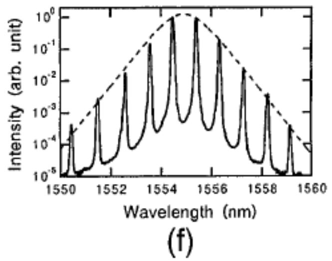
September 15, 1997 / Vol. 22, No. 18 / OPTICS LETTERS

Eiji Yoshida and Masataka Nakazawa



115-GHz pulse train





Vol. 15, No. 4/April 1998/J. Opt. Soc. Am. B

Passive mode locking by dissipative four-wave mixing

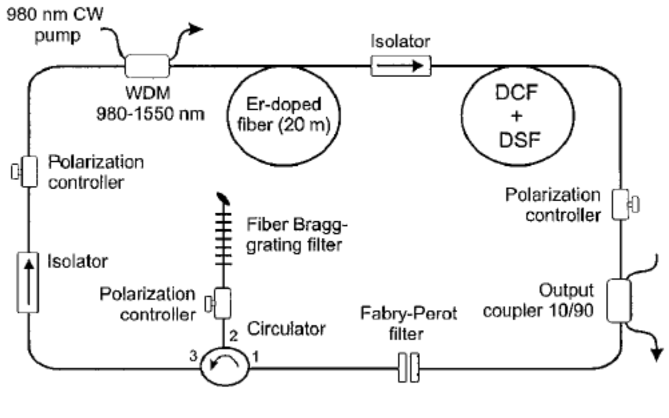
M. Quiroga-Teixeiro, C. Balslev Clausen, M. P. So”rensen, and P. L. Christiansen, P. A. Andrekson

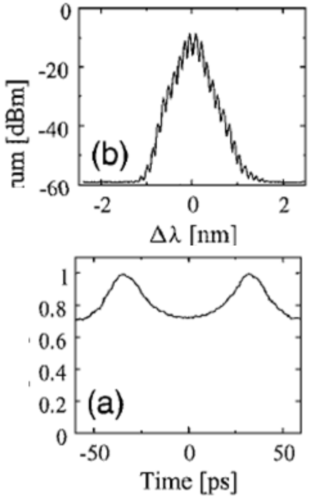
Theoretical description

OPTICS LETTERS / Vol. 27, No. 7 / April 1, 2002

Self-induced modulational instability laser revisited: normal dispersion and dark-pulse train generation

Thibaut Sylvestre,* Stéphane Coen, Philippe Emplit, and Marc Haelterman

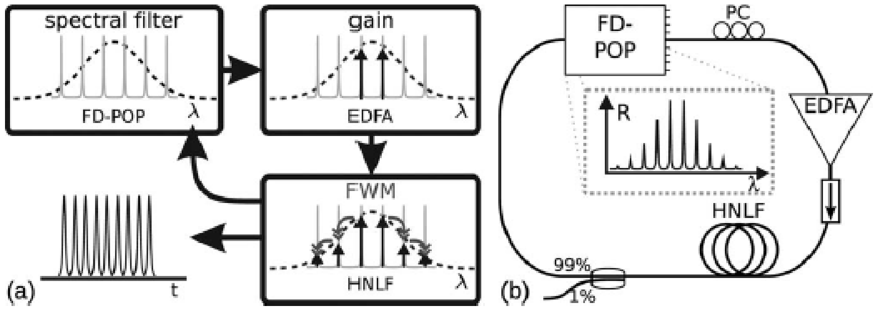




OPTICS LETTERS / Vol. 34, No. 24 / December 15, 2009

Repetition-rate-selective, wavelength-tunable mode-locked laser at up to 640 GHz

Jochen Schröder,* Trung D. Vo, and Benjamin J. Eggleton

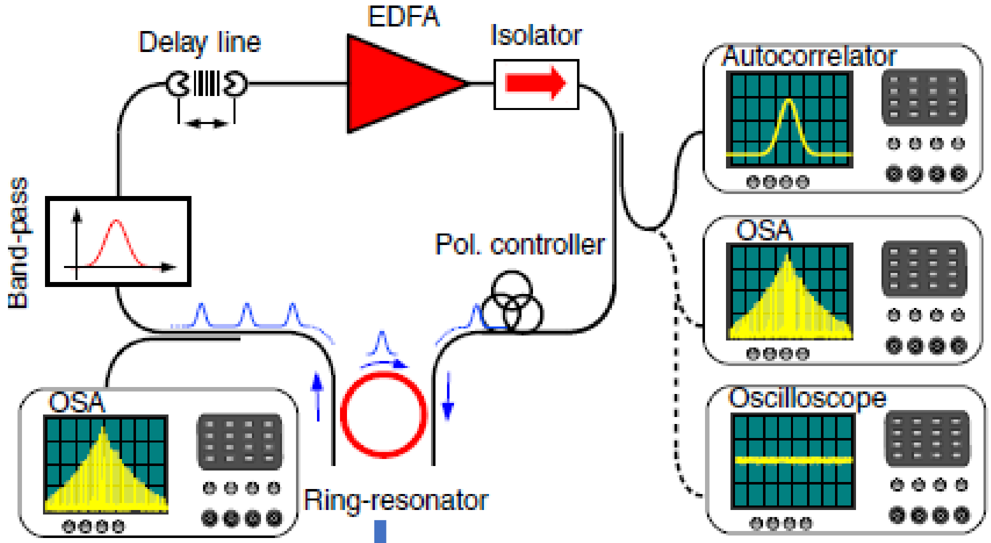


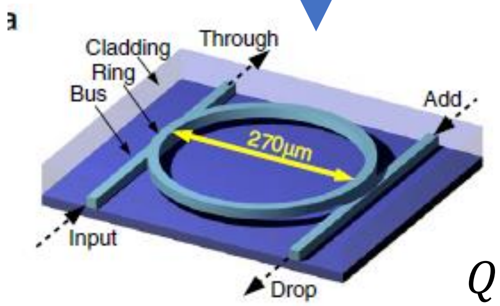
nature COMMUNICATIONS 3,765, 2012
OPEN

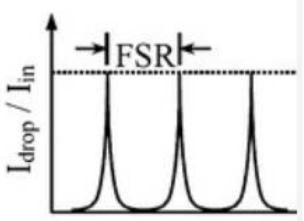
Main claim: FWM can happen in microcavity, thus no long fiber needed

Demonstration of a stable ultrafast laser based on a nonlinear microcavity

M. Peccianti[1,2], A. Pasquazi[1], Y. Park[1], B.E. Little[3], S.T. Chu[3,4], D.J. Moss[1,5] & R. Morandotti[1]



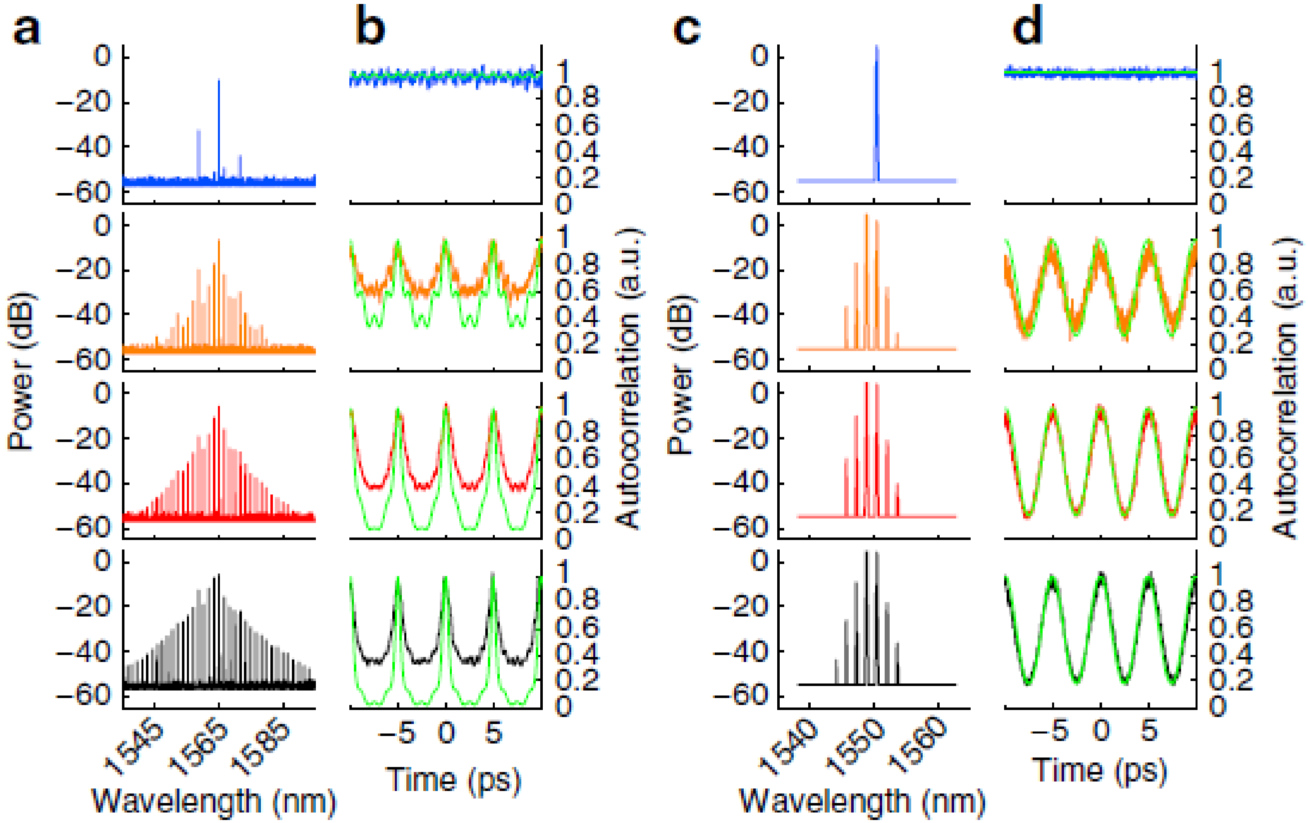




$Q = 1.2 \times 10^6$

FSR=200 GHz

$\mathrm{FSR}_{\mathrm{laser}} = 6\ \mathrm{MHz}$ $\mathrm{FSR}_{\mathrm{laser}} = 64\ \mathrm{MHz}$



Stable and unstable regimes observed depending on the delay line position

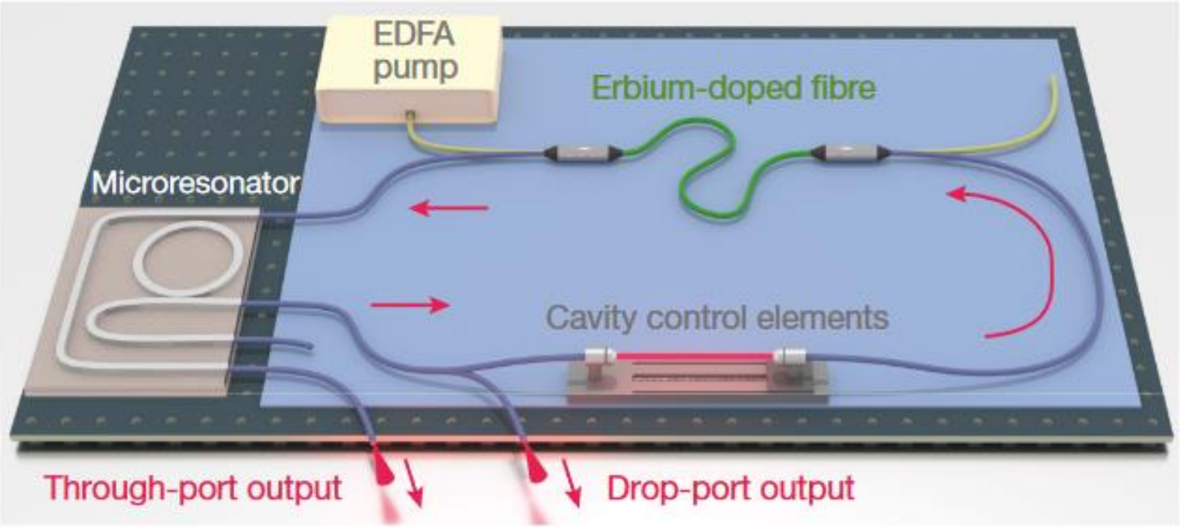
nature

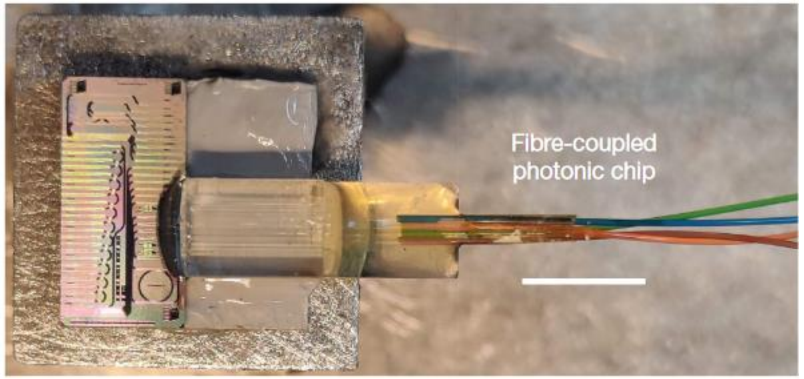
Self-emergence of robust solitons in a microcavity

Nature | Vol 608 | 11 August 2022 | 303

Maxwell Rowley[1], Pierre-Henry Hanzard[1], Antonio Cutrona[1,2], Hualong Bao[1], Sai T. Chu[3], Brent E. Little[4], Roberto Morandotti[5], David J. Moss[6], Gian-Luca Oppo[7], Juan Sebastian Totero Gongora[1,2], Marco Peccianti[1,2] & Alessia Pasquazi[1,2]✉

Main claim: Fine tuning of laser cavity parameters makes soliton a main attractor

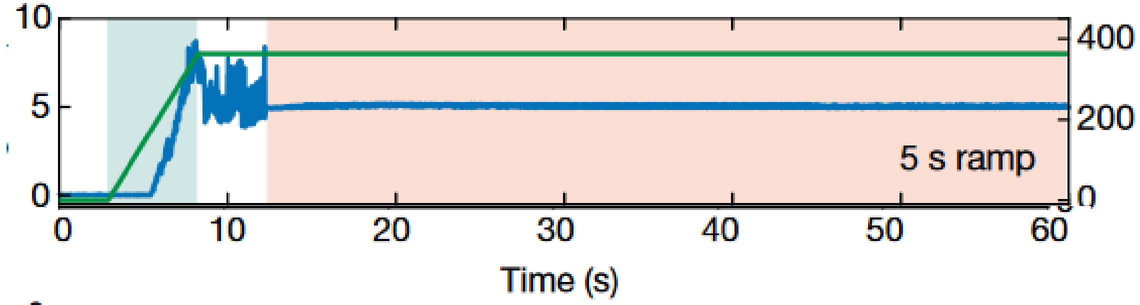


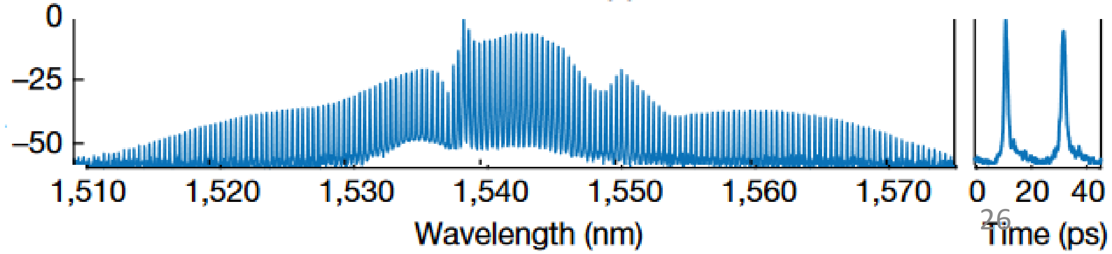


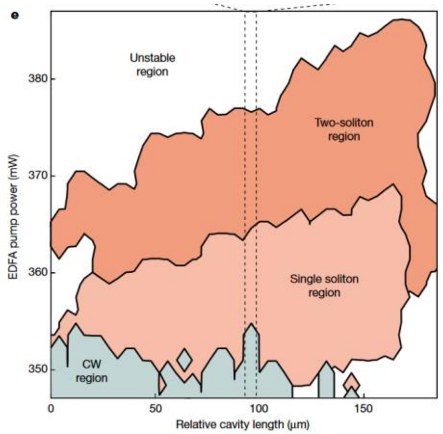
$$FSR_{cavity} = 49.8\ GHz$$

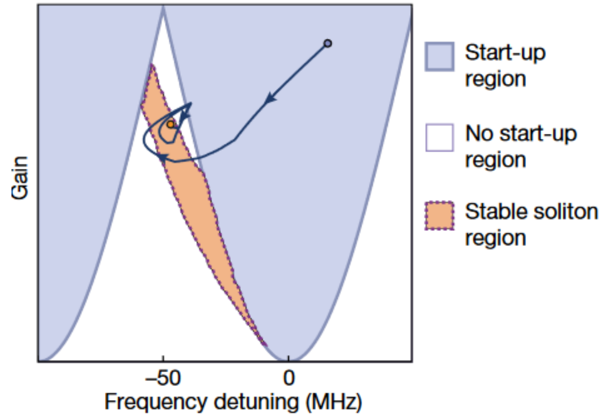
$$Linewidth = 120\ MHz$$

$$FSR_{laser} = 95\ MHz$$









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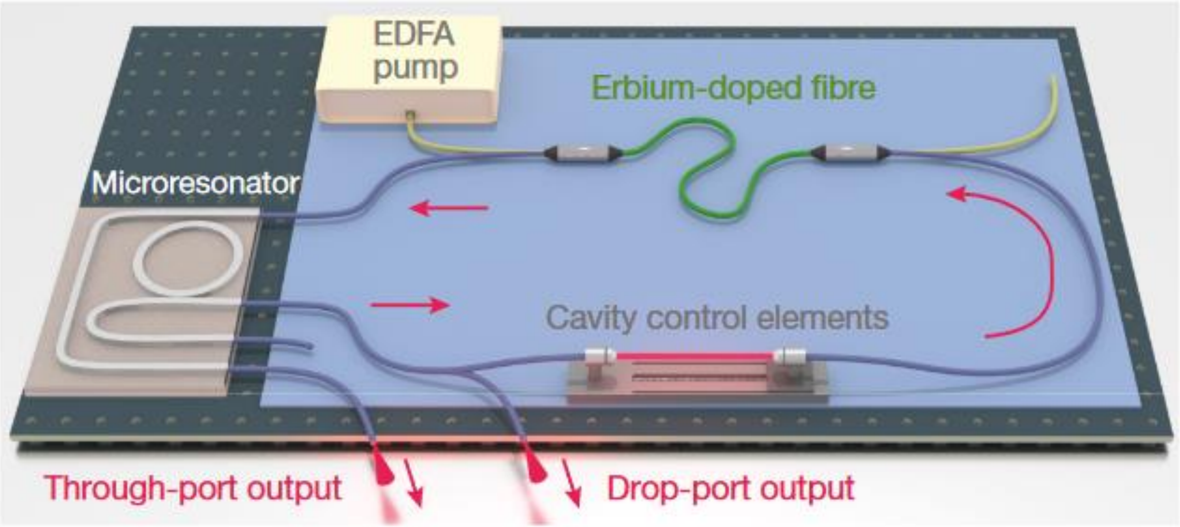

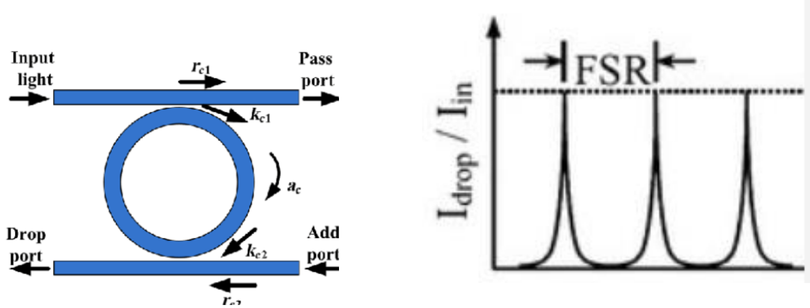

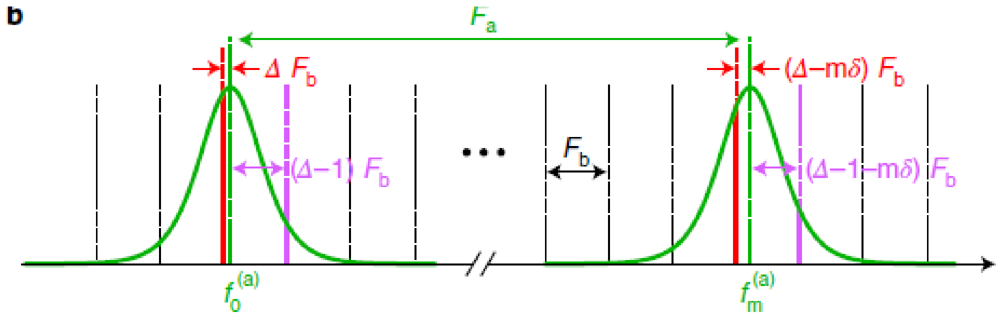

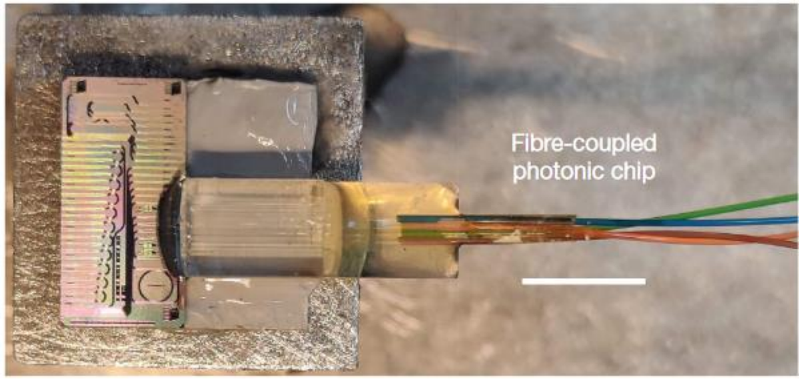

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$$Linewidth = 120\ MHz$$

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Microring has two roles:

- Increase spectra by four wave mixing
- Filter laser modes to leave only every Nth mode

nature

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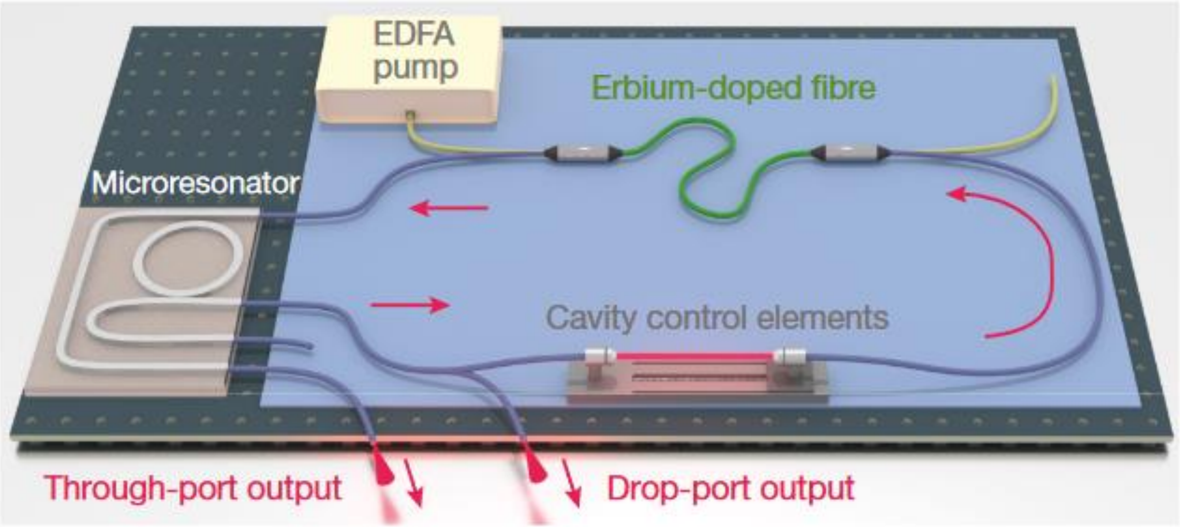

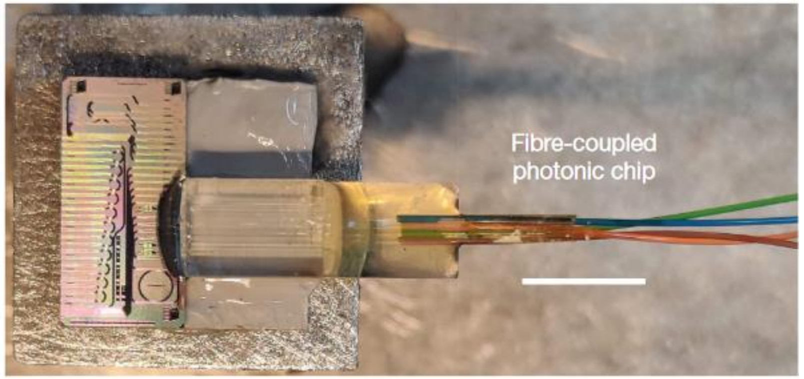

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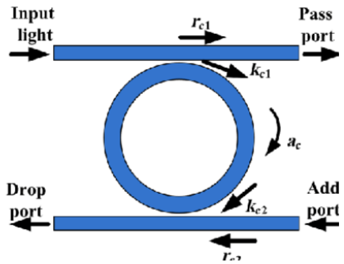

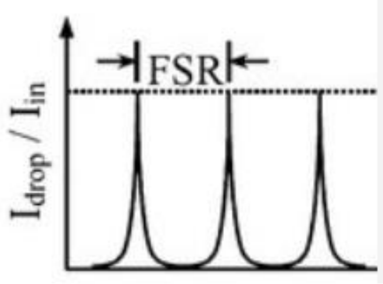

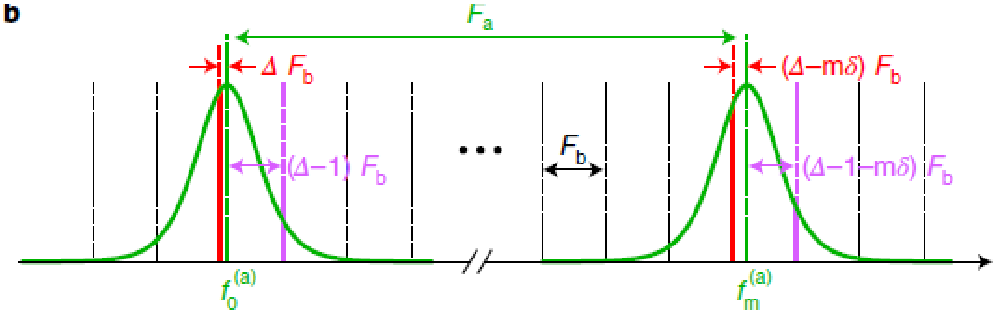

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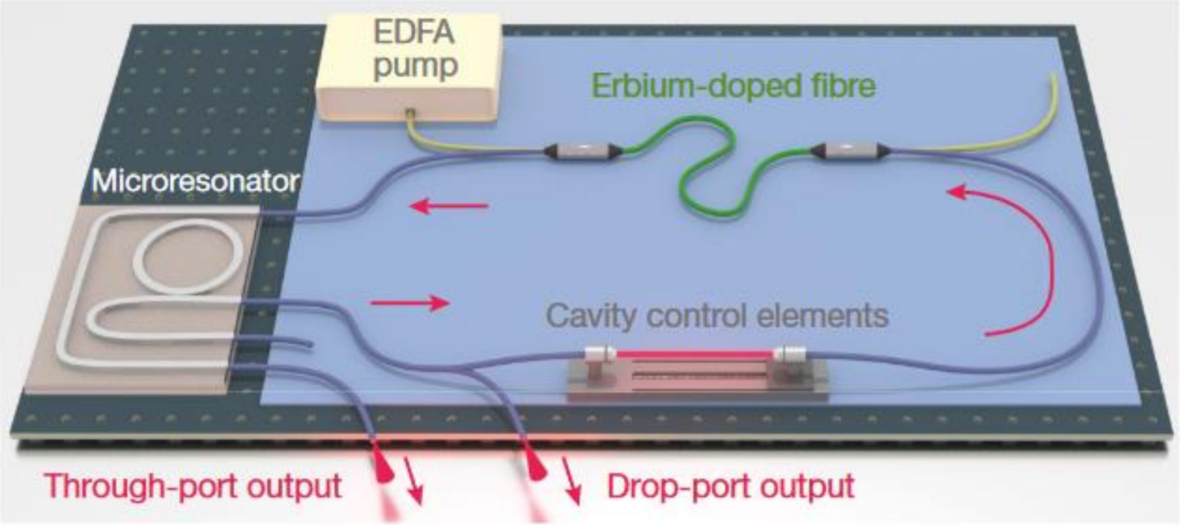

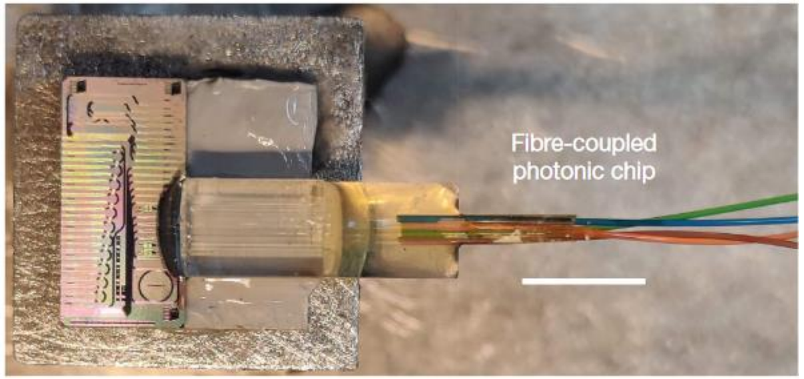

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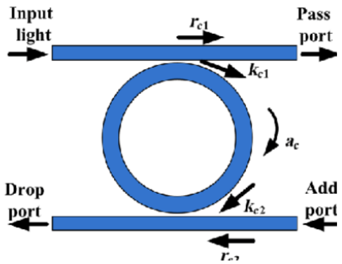
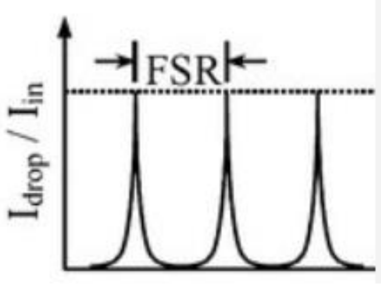
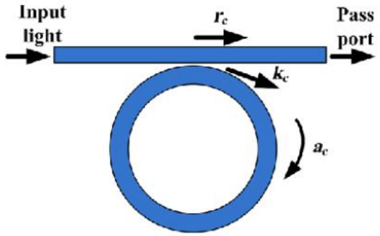
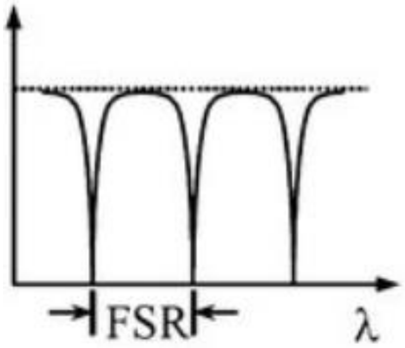




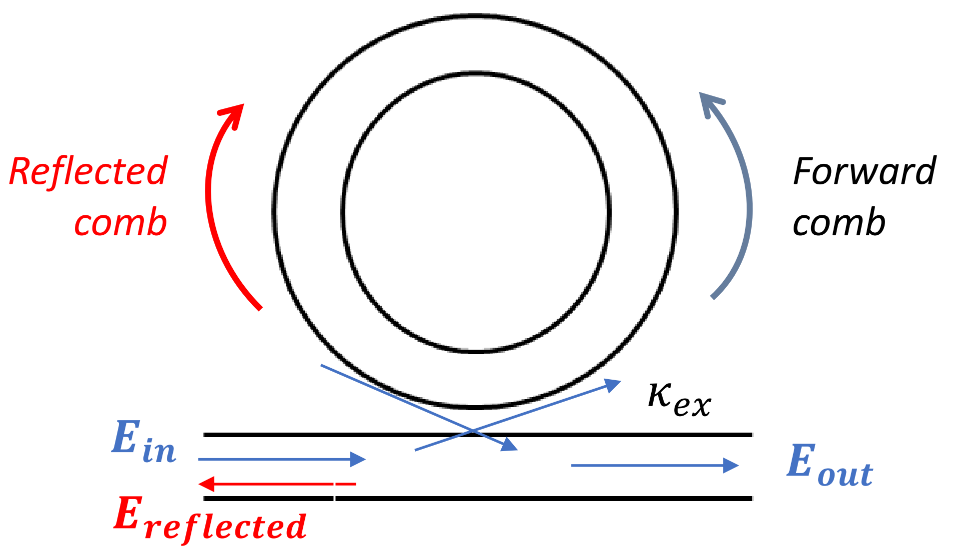
Is it possible to use 2-port microcavity?



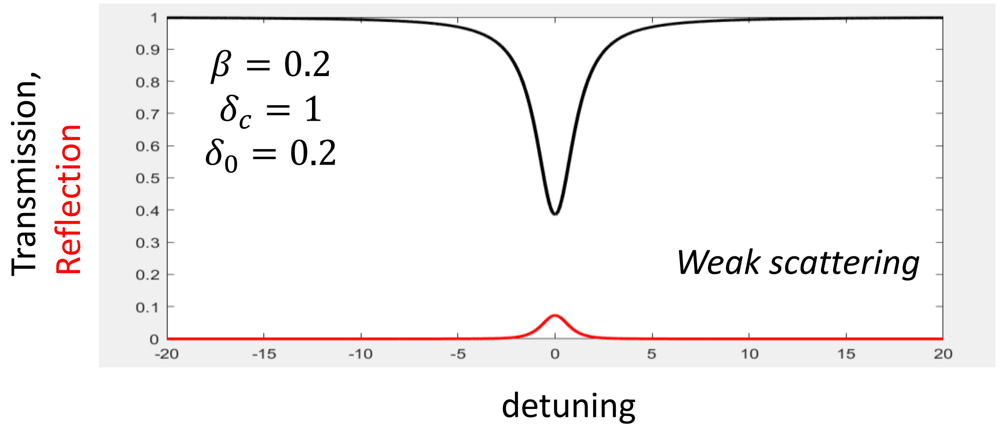


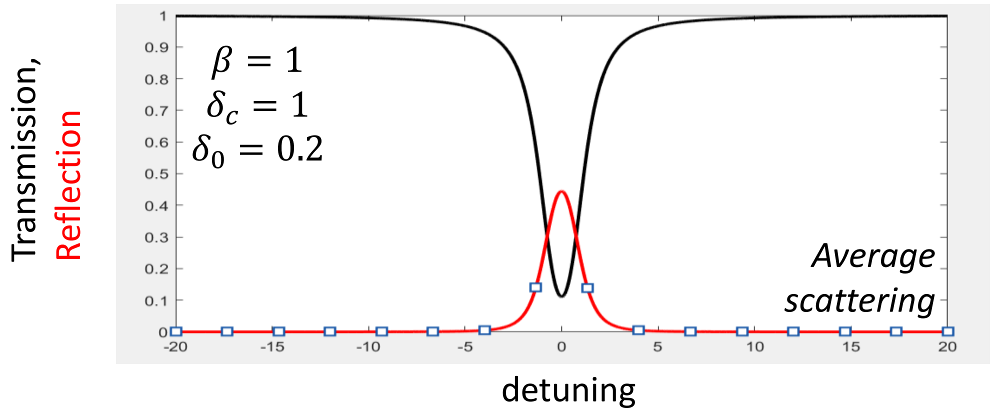
Spontaneous creation of reflected comb

One more player - **Rayleigh scattering**

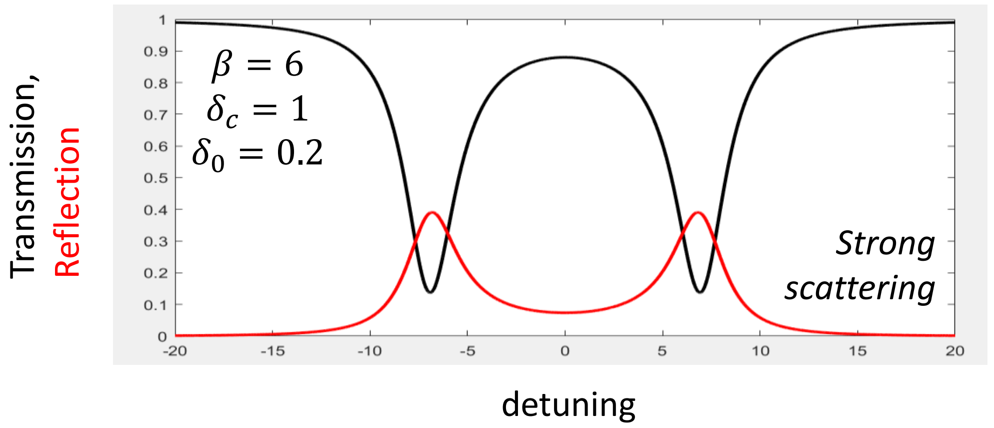


In high-Q microcavity **Rayleigh scattering** is enhanced by factor, similar to **Purcell factor** -> spontaneous back reflected comb formation.





β – *Rayleigh scattering*
δ_c – *coupling losses*
δ_0 – *cavity losses*

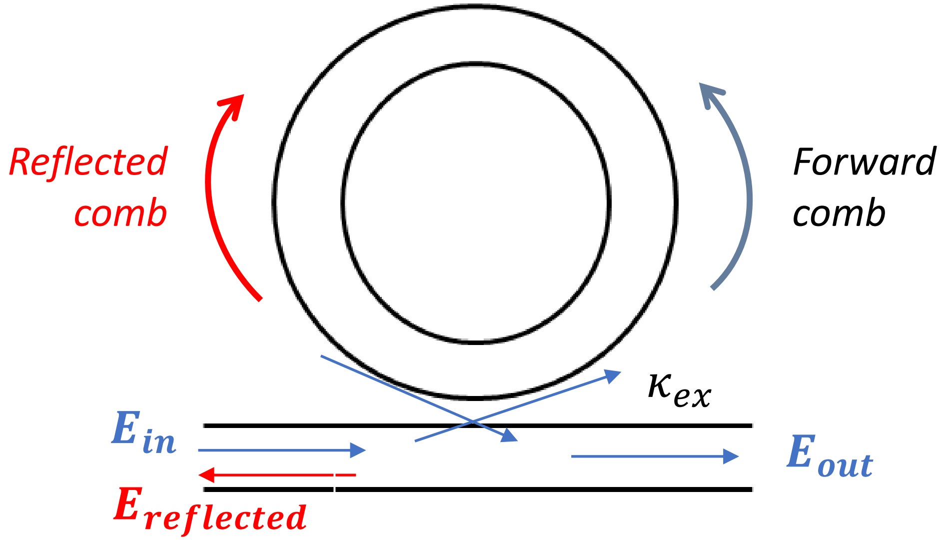


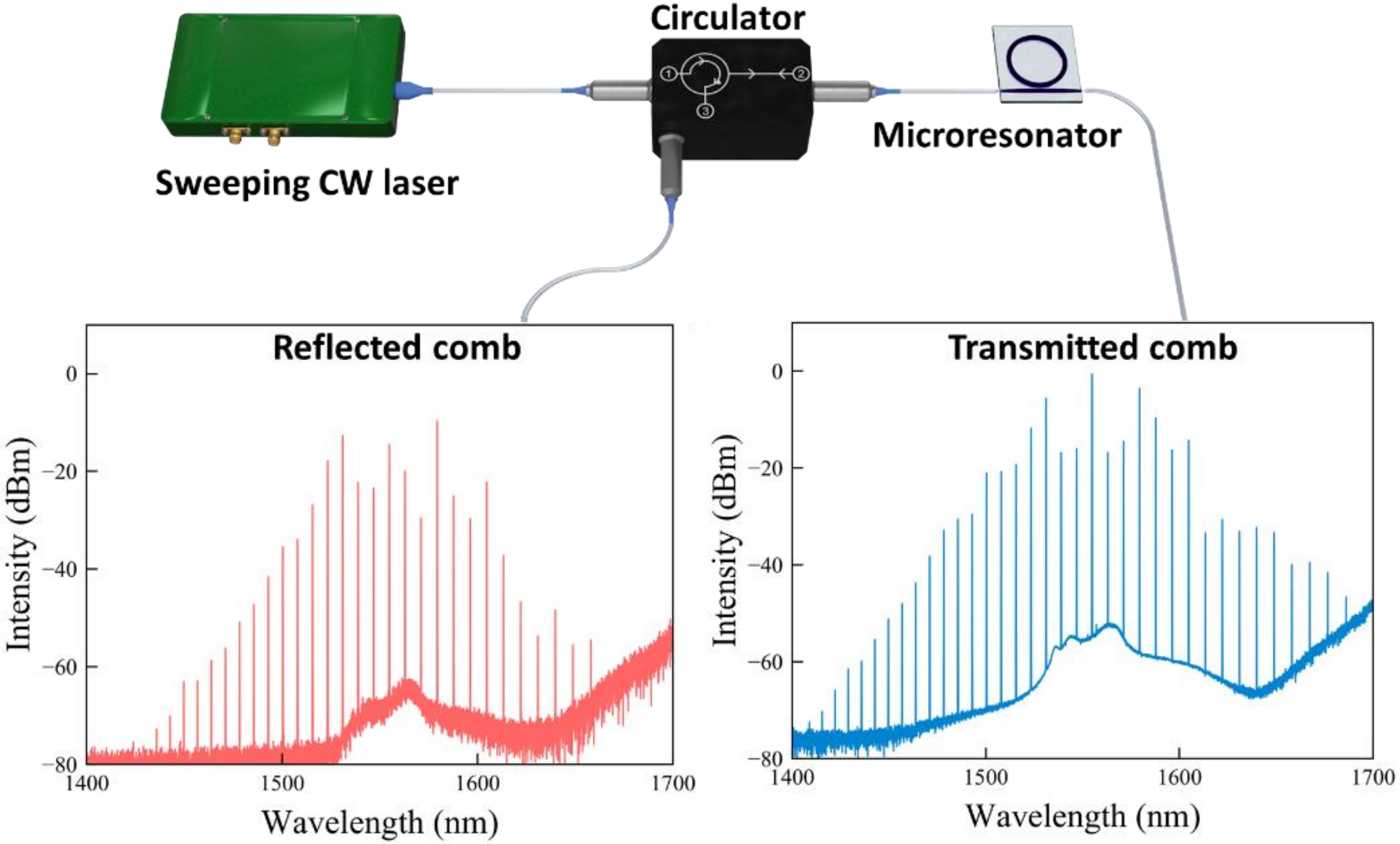
Kippenberg T. J., Spillane S. M., Vahala K. J. Opt. Lett. V. 27, 2002. P. 1669-1671

Spontaneous creation of reflected comb

Igor Bilenko

One more player - **Rayleigh scattering**





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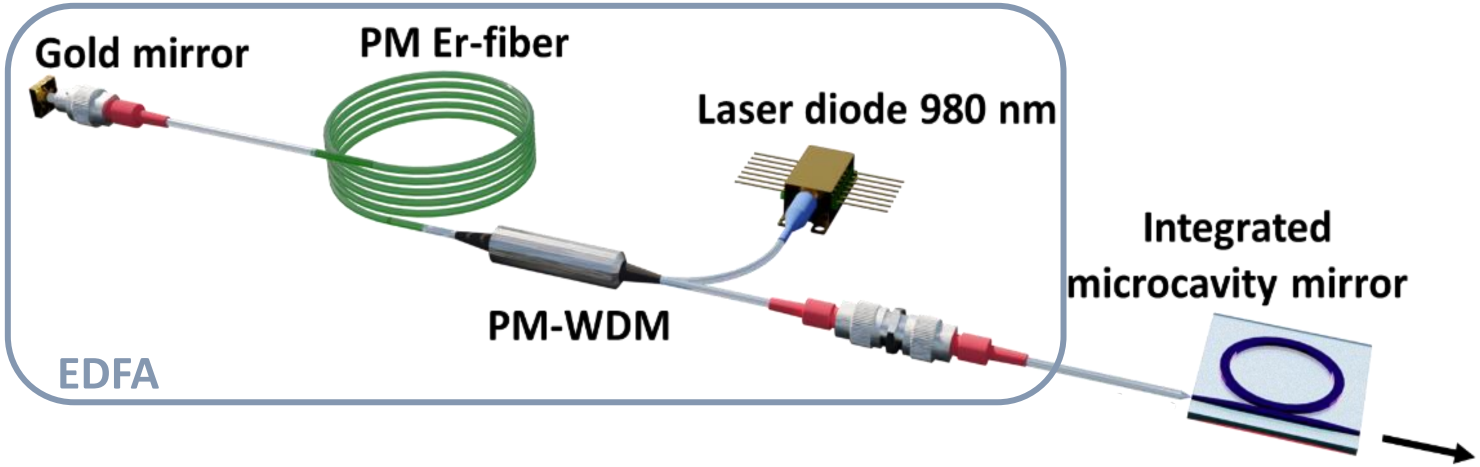
Kippenberg T. J., Spillane S. M., Vahala K. J. Opt. Lett. V. 27, 2002. P. 1669-1671

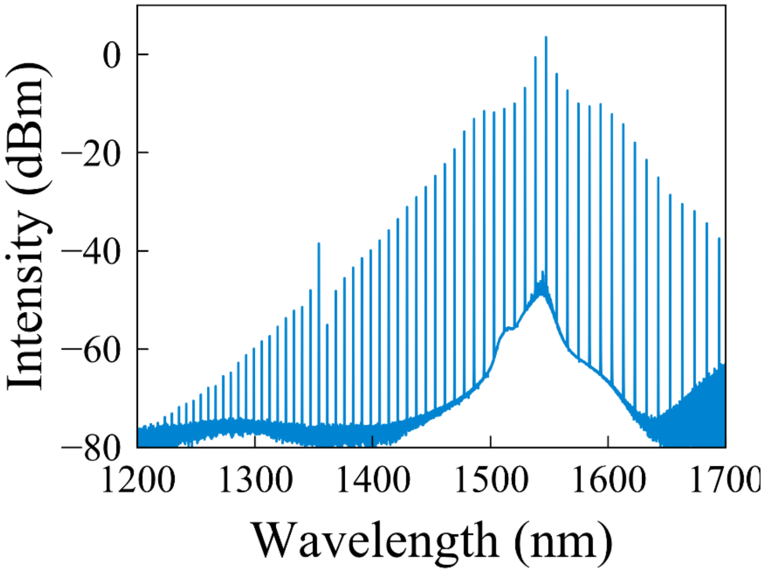
Microcavity as a semi-reflective mirror

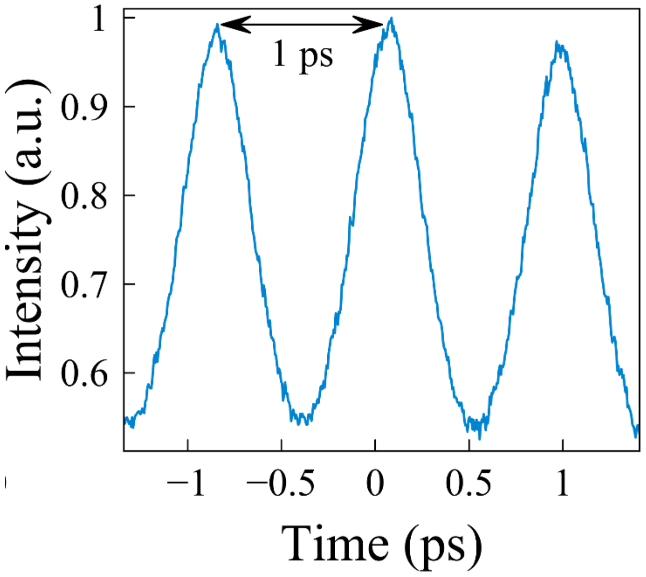


$FSR_{laser} = 35\ MHz$

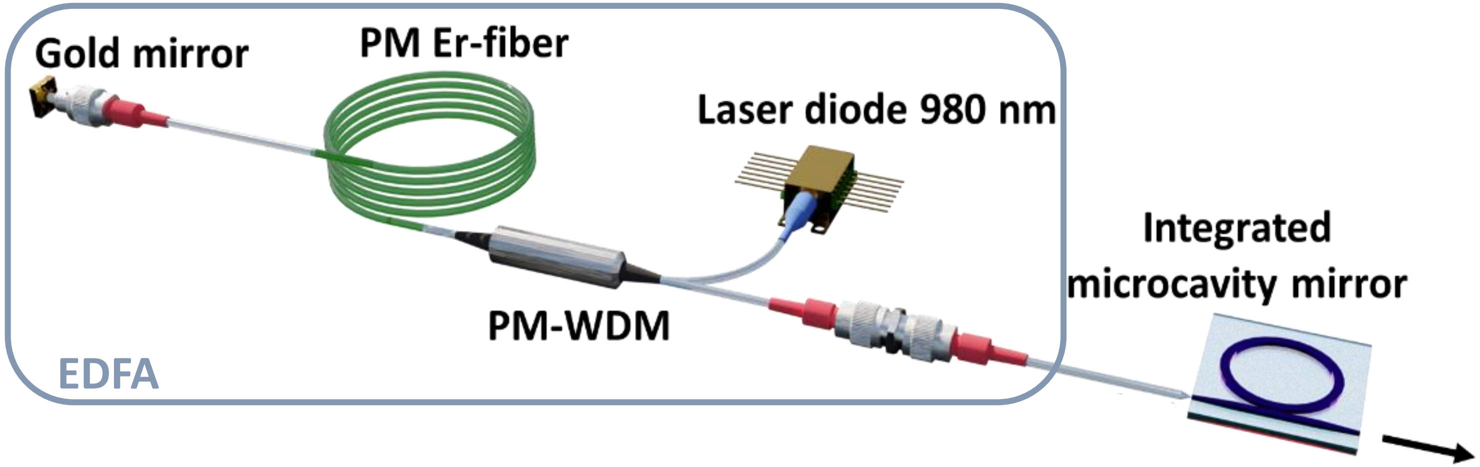
$FSR_{cavity} = 1\ THz$

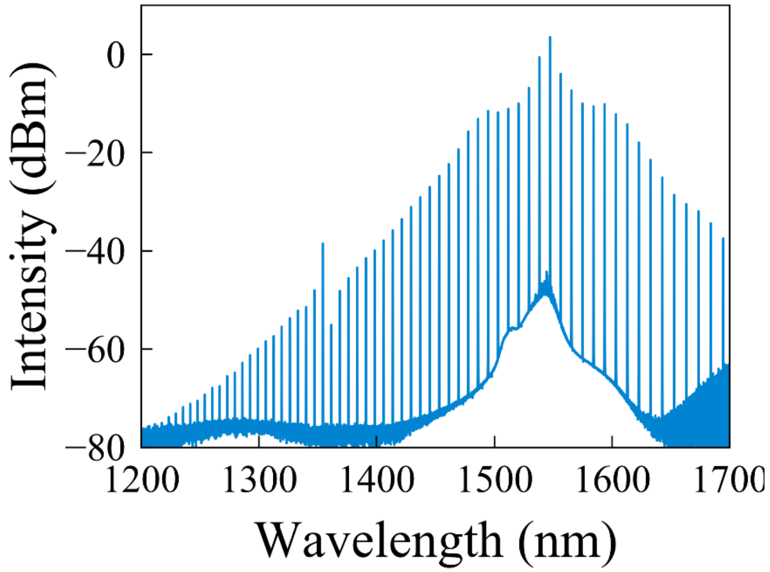
$Linewidth = 150\ MHz$

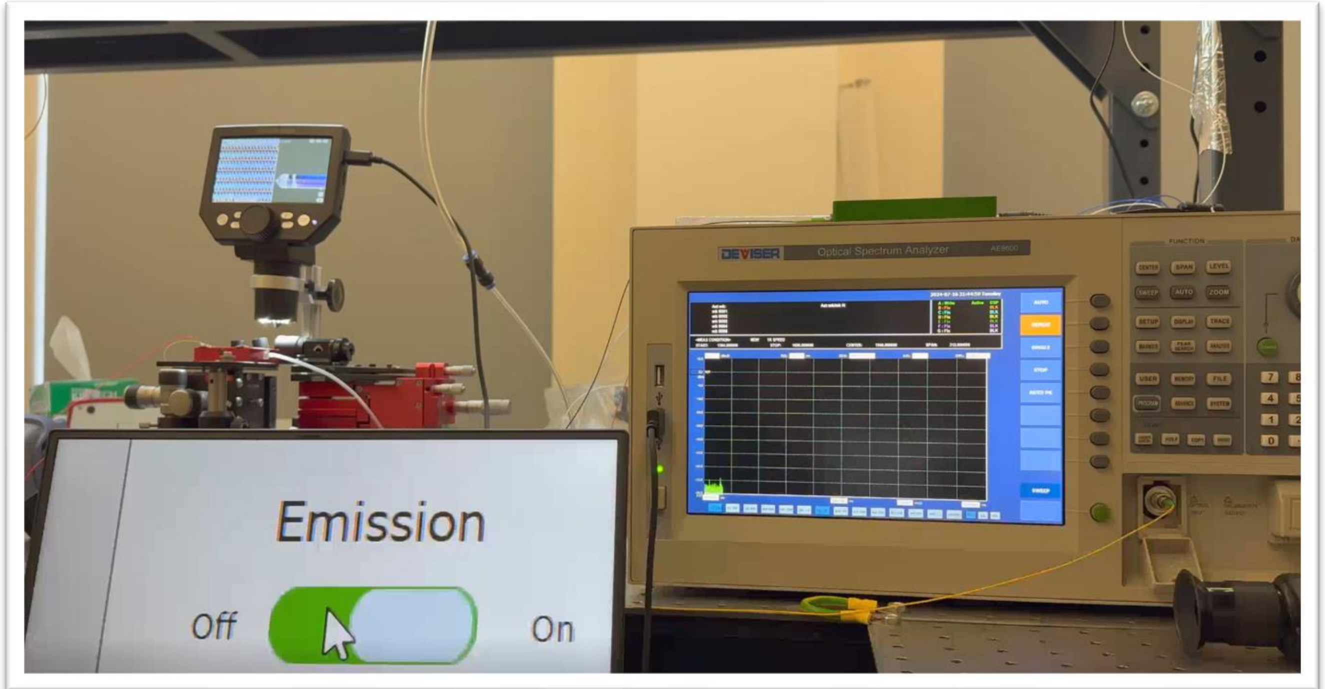


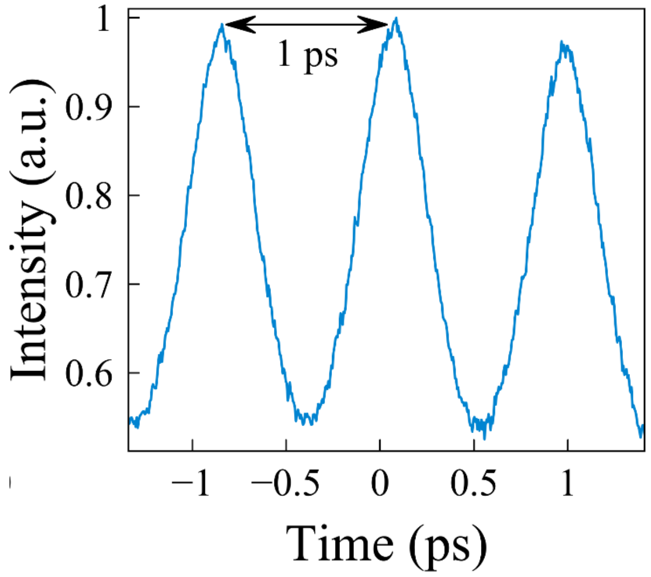


Microcavity as a semi-reflective mirror

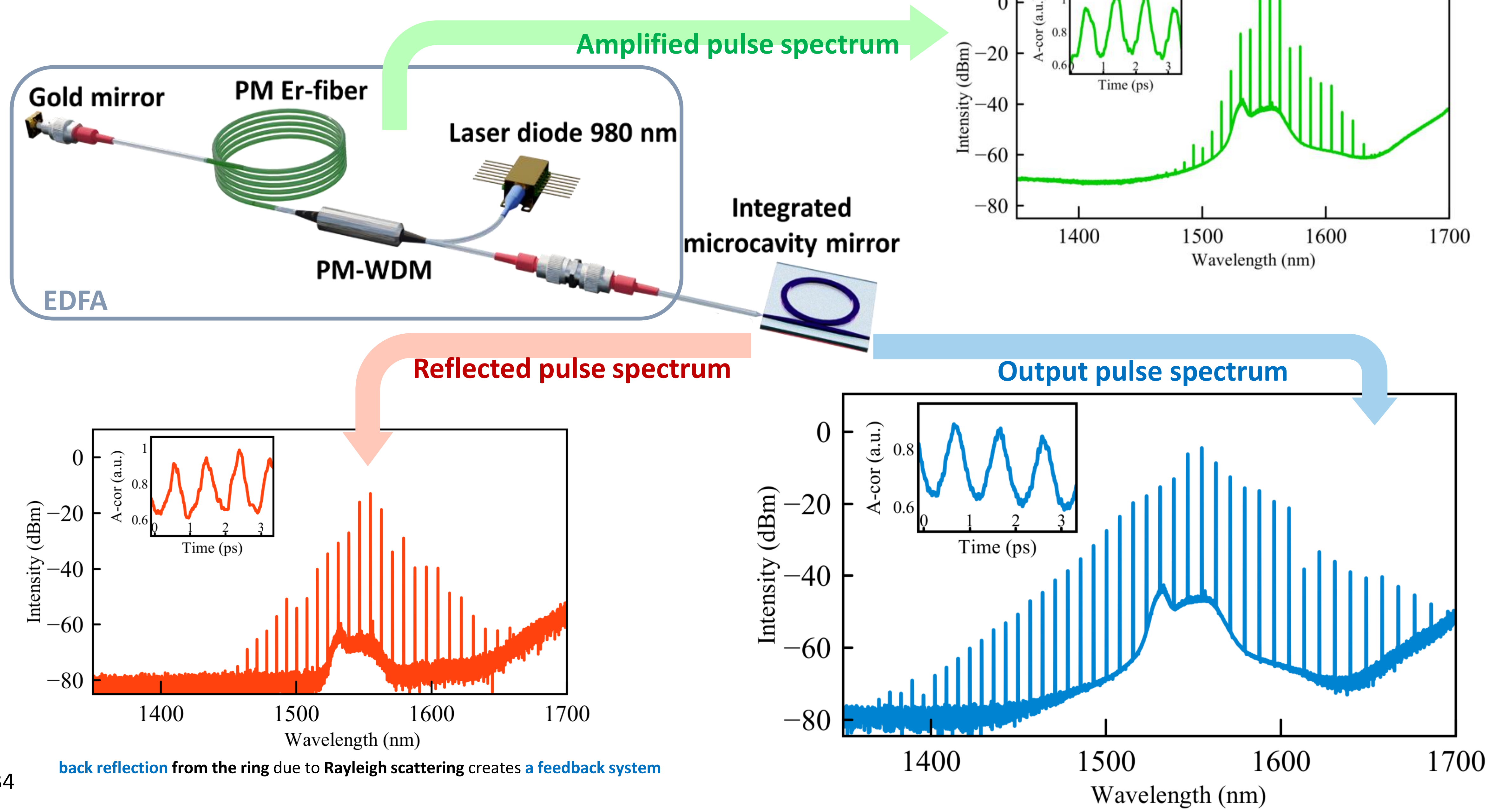








Microcavity as a semi-reflective mirror



back reflection from the ring due to **Rayleigh scattering** creates **a feedback system**

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Thank you for
your attention!