Kerr optical frequency comb generation in micro-resonators

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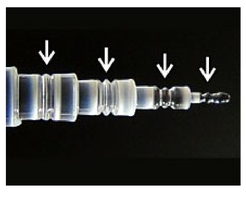
Introduction

- Ultra-high Q-factor silica resonator
- Frequency comb generated through Kerr nonlinearity
- Theoretical model: Lugiato-Lefever equation
- Intriguing and unexplained phase-locked states
- New characterization setup: phase and detuning measurement

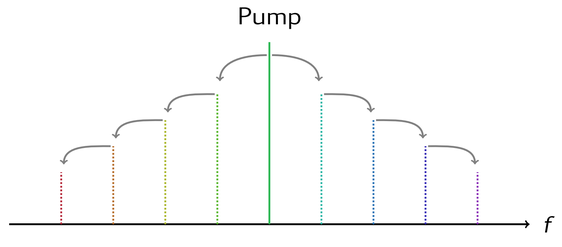
Silica whispering-gallery-mode resonators [1]

- CO_2-laser-machined fused-silica rod
- Diameter: 0.2-4 mm ⇒ FSR: 15-300 GHz
- Q-factor $\sim 1 \times 10^8$
- Tapered-fiber coupling for high efficiency



Kerr comb generation

- Degenerate and non-degenerate four-wave mixing
- New frequencies generated close to resonances
- Cascaded process ⇒ Kerr comb generation

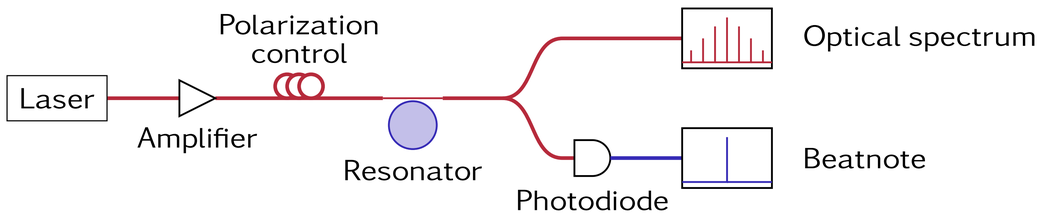


$$\hbar\omega_1 + \hbar\omega_2 \rightarrow \hbar\omega_3 + \hbar\omega_4$$

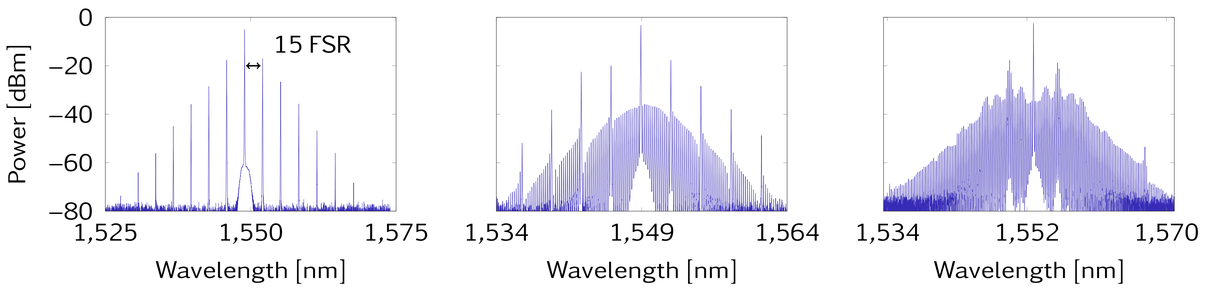
- Understand nonlinear phase-locking mechanism

Experiments

- Amplified CW laser, $P \sim 100$ mW



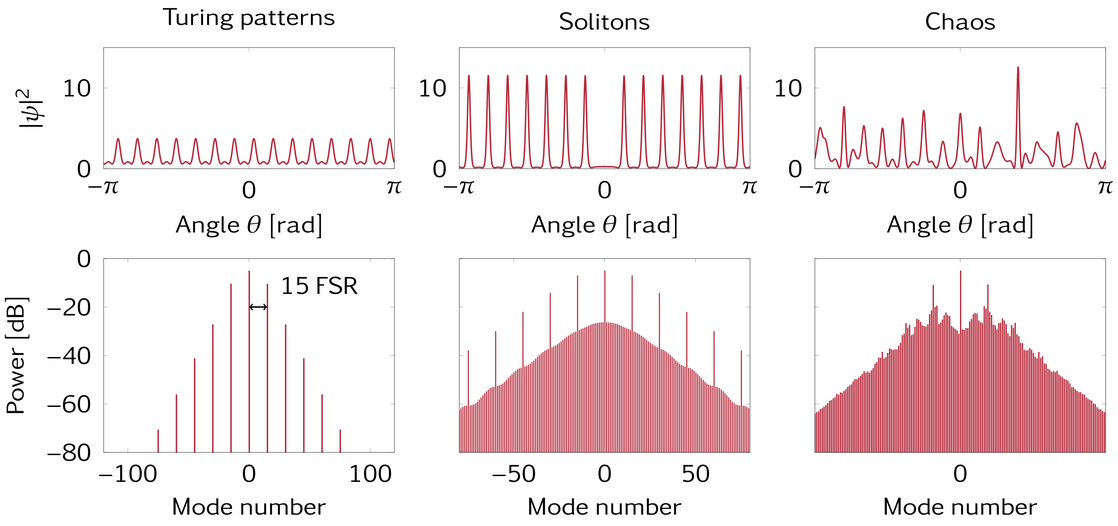
- Various regimes depending on:
  - detuning,
  - pump power,
  - polarization,
  - coupling position, ...



Model: Lugiato-Lefever equation [2]

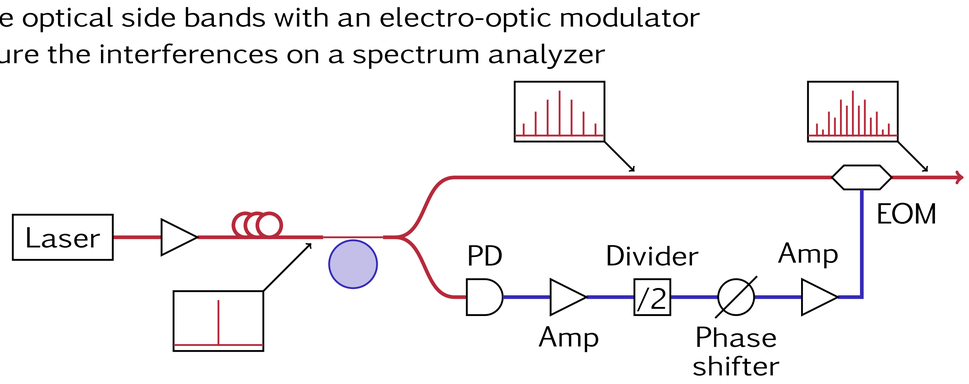
- Slowly-varying envelope of the intra-cavity field
- Spatio-temporal description
- Nonlinear Schrödinger equation with damping and driving
- Losses, detuning α, nonlinearity, dispersion β, driving F

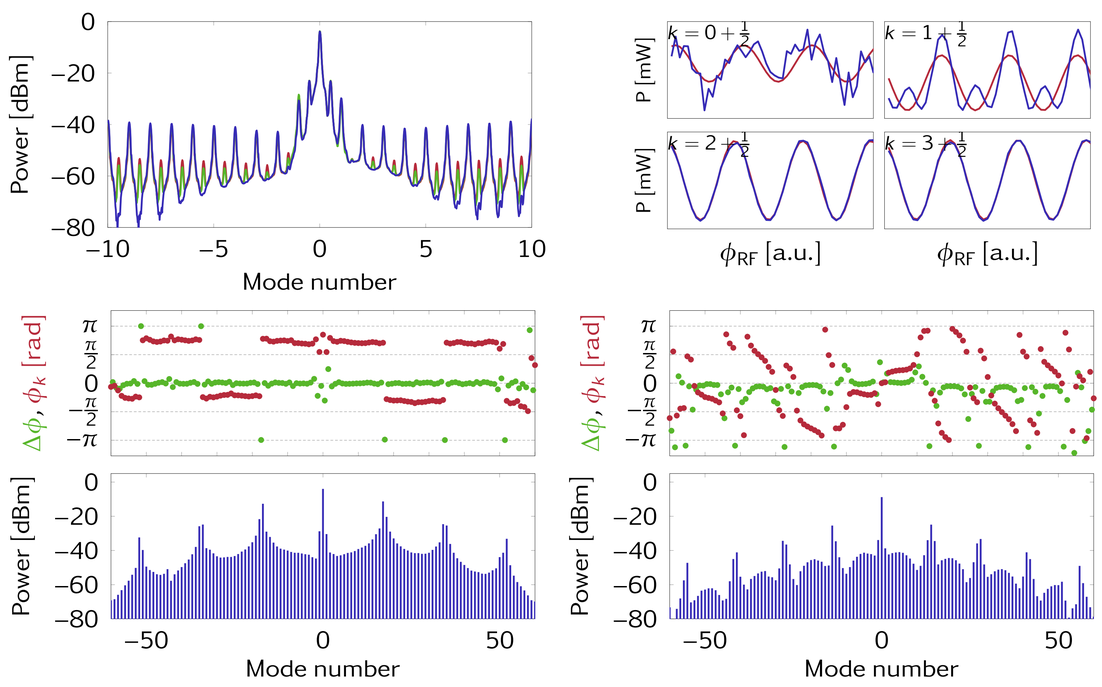
$$\frac{\partial \psi}{\partial \tau} = -(1 + \mathrm{i}\alpha)\psi + \mathrm{i}|\psi|^2\psi - \mathrm{i}\frac{\beta}{2}\frac{\partial^2 \psi}{\partial \theta^2} + F$$



Measurement of the optical phases

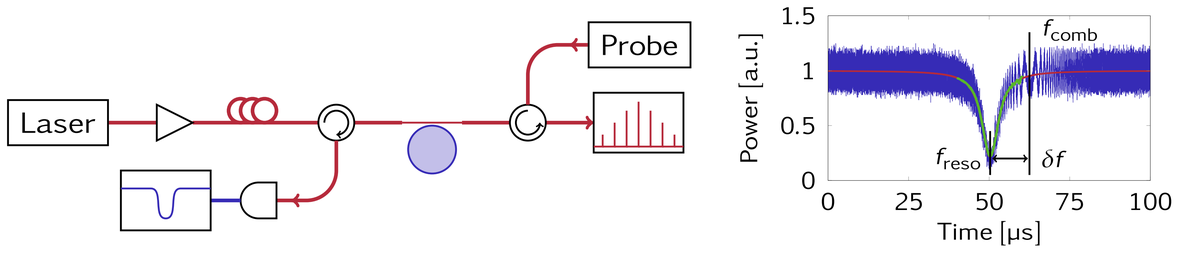
- $f_c/2$ interferometry:
  - Detect comb beatnote at f_c
  - Generate $f_c/2$
  - Create optical side bands with an electro-optic modulator
  - Measure the interferences on a spectrum analyzer

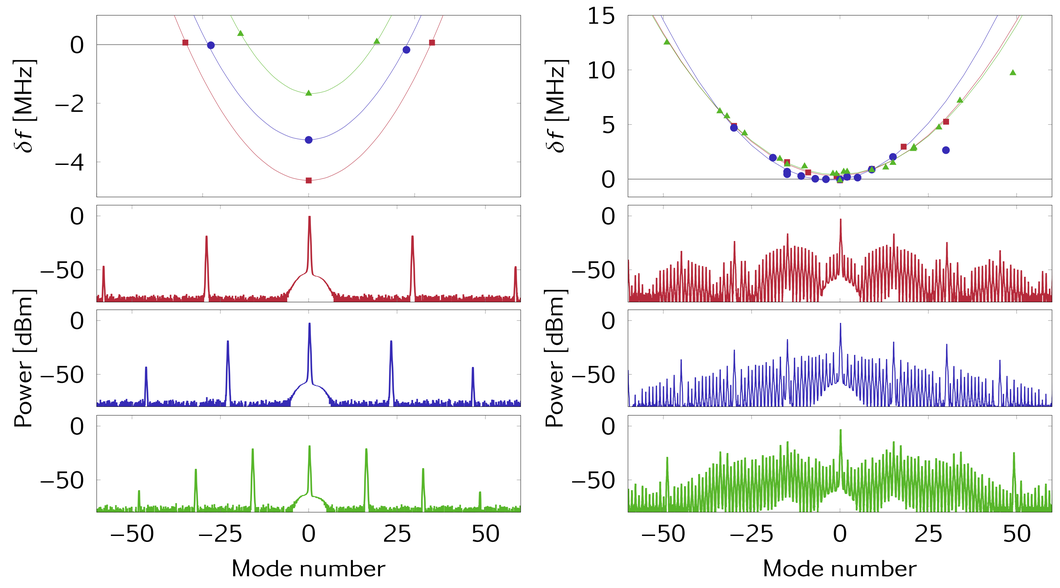




Detuning of the comb's lines [3]

- Dispersion ⇒ inequidistant resonances ⇒ comb line ≠ resonance
- Measure detuning $\delta f = f_{reso} - f_{comb}$
  - Sweeping, backward probe laser
  - Beatnote with back-scattered comb lines





- δf fit parabola ⇒ second order dispersion $\tilde{D}_2 \simeq 12$ kHz/FSR
- First mode of Turing patterns close to $\delta f = 0$
- Some detunings off-fit: mode crossing

1. P. Del'Haye, S. A. Diddams, and S. B. Papp, "Laser-machined ultra-high-q microrod resonators for nonlinear optics," *Applied Physics Letters* **102,** 221119 (2013).
2. K. Chembo and C. R. Menyuk, "Spatiotemporal lugiato-lefever formalism for kerr-comb generation in whispering-gallery-mode resonators," *Phys. Rev. A* **87,** 053852 (2013).
3. P. Del'Haye, A. Coillet, W. Loh, K. Beha, S. B. Papp, and S. A. Diddams, "Phase Steps and Hot Resonator Detuning in Microresonator Frequency Combs," *ArXiv* **1405.6972** (2014).