High-Energy Passive Mode-Locking with Ginzburg-Landau Models

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Ring Cavity Lasers

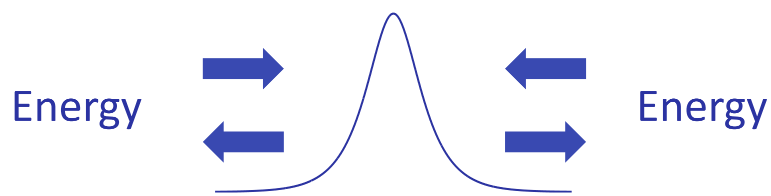
- Optical Solitons (Hasegawa & Tappert, 1973)

  - Balance between Kerr effect and dispersion

$$i\frac{\partial\psi}{\partial z} + \frac{D}{2}\frac{\partial^2\psi}{\partial t^2} + \gamma|\psi|^2\psi = 0$$

- “Dissipative” Solitons (Perturbed Nonlinear Schrödinger)

  - Localized pulses under the influence of dissipation

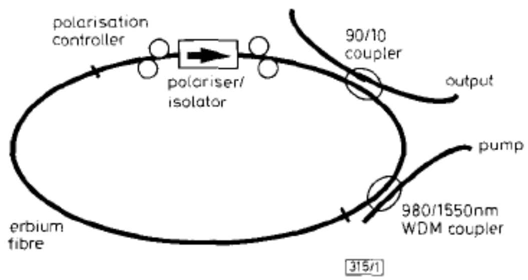


  - Achieved using mode-locked lasers

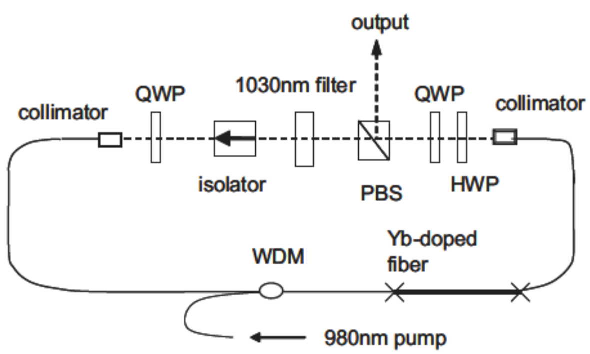
Akhmediev & Ankiewicz, "Solitons: Nonlinear pulses and beams," Chapman & Hall

Ring Cavity Lasers

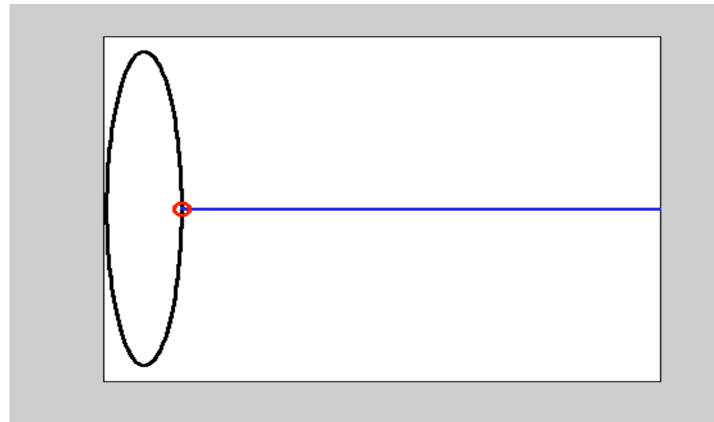
- Mode-Locking: generation of ultrashort pulses



Tamura, Haus, and Ippen, "Self-starting additive pulse mode-locked erbium fiber ring laser," Electron. Lett. **28**, 2226 (1992)



Chong, Buckley, Renninger, and Wise, "All-normal-dispersion femtosecond fiber laser," Opt. Exp. **14**, 10095 (2006)



- Nonlinear fiber
- Saturable absorber
  (Intensity discrimination)
- Output coupler
- Gain medium

Polarizer

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Ring Cavity Lasers

- Master Mode-Locking Model (Haus *et al*, 1991)

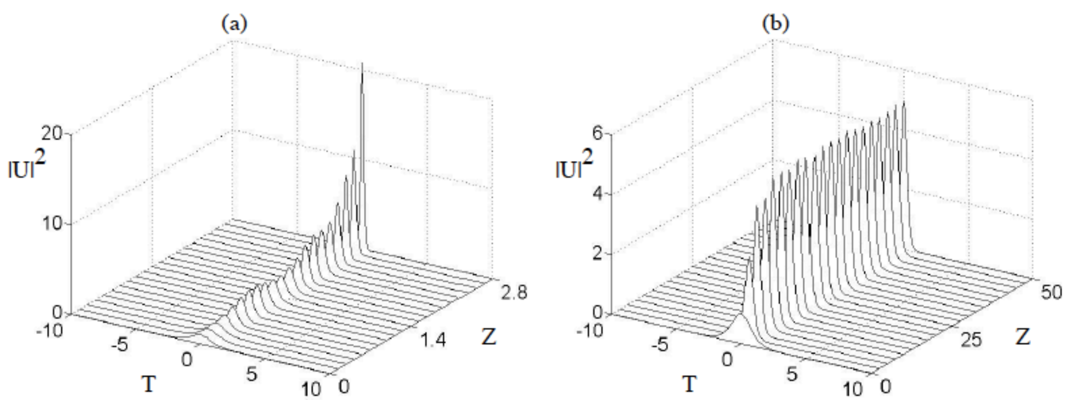
Dispersion | Saturating gain | Loss

$$i\frac{\partial\psi}{\partial z}+\frac{D}{2}\frac{\partial^2\psi}{\partial t^2}+\gamma|\psi|^2\psi+\nu|\psi|^4\psi = ig(z)\left(1+\tau\frac{\partial^2}{\partial t^2}\right)\psi - i\delta\psi + \boxed{i\beta|\psi|^2\psi + i\mu|\psi|^4\psi}$$

Kerr effect | Gain bandwidth | Saturable absorber

NLS

Perturbation



$$g(z)=\frac{2g_0}{1+\|\psi\|^2/e_0}$$

Mode-Locking Operation

$$\boxed{\beta > 0 > \mu}$$

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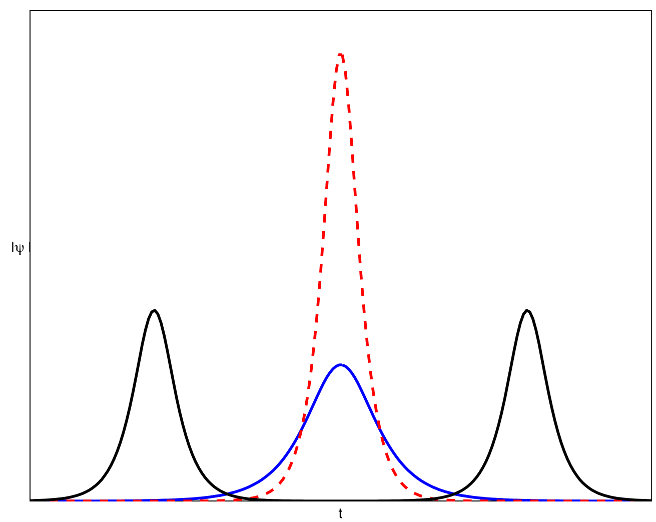
Ring Cavity Lasers

- Advantages of fiber lasers
  - Relatively cheap
  - Don’t require careful alignment
  - Compact
- Limited energy output (e.g. ~0.1nJ in the case of NLS solitons)

Renninger, Chong, and Wise, “Area theorem and energy quantization for dissipative optical solitons,” J. Opt. Soc. Am. B **27**, 1978 (2010)

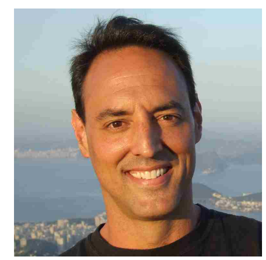


Multi-pulsing instability

1. Dissipative Soliton Resonance

Ding, Grelu, and Kutz, "Dissipative Soliton Resonance in a Passively Mode-Locked Fiber Laser," Opt. Lett. **36**, 1146 (2011)

Varying Dispersion



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Université de Bourgogne

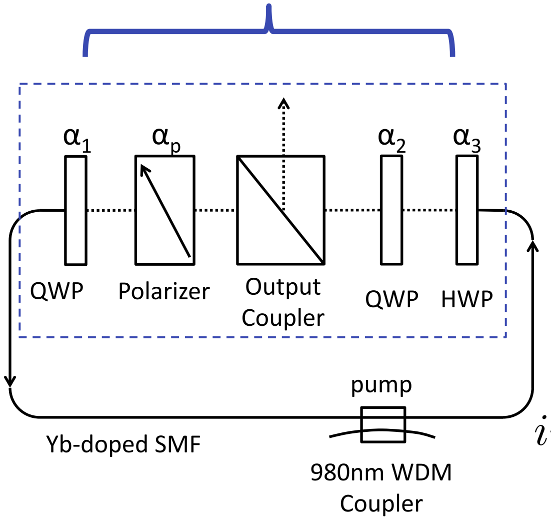
Nathan Kutz
University of Washington

High-Energy Mode-Locking

- Physically realizable model

$$\boxed{w \propto |\psi|^2}$$

Periodic transmission



$$\begin{aligned} Q = & \frac{1}{2}\left\{e^{-iK}\left[\cos(2\alpha_2 - 2\alpha_3 - \alpha_p) + i\cos(2\alpha_3 - \alpha_p)\right]\right. \\ & \times \left[i\cos(2\alpha_1 - \alpha_p - w) - \cos(\alpha_p - w)\right] \\ & + e^{iK}\left[\sin(2\alpha_2 - 2\alpha_3 - \alpha_p) - i\sin(2\alpha_3 - \alpha_p)\right] \\ & \left.\times \left[\sin(\alpha_p - w) - i\sin(2\alpha_1 - \alpha_p - w)\right]\right\} . \end{aligned}$$

Averaging

$$i\psi_z + \frac{D}{2}\psi_{tt} + |\psi|^2\psi = ig(z)\left(1 + \tau\partial_t^2\right)\psi - i\Gamma\psi + i(\log Q)\psi$$

$$\alpha_1 = 0.7863\pi$$
$$\alpha_2 = 0.3\pi$$
$$\alpha_3 = \alpha_p = 0$$

Taylor Series

$$\nu = -0.08$$
$$\delta = 2.45$$
$$\beta = 0.36$$
$$\mu = -0.07$$

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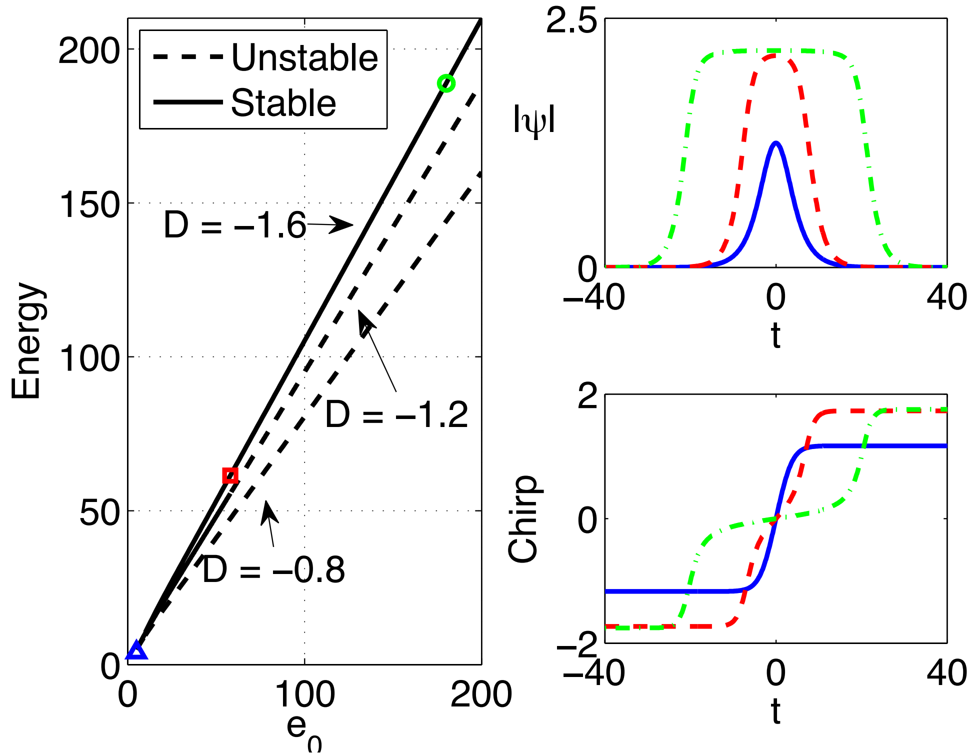
Ding and Kutz, "Operating regimes, split-step modeling, and the Huas master mode-locking model," J. Opt. Soc. Am. B **26**, 2290 (2009)

High-Energy Mode-Locking

- DSR is practically achievable



- Critical dispersion $D_c \approx -1.2$
- Multi-pulsing occurs quickly when $D > D_c$
- Multi-pulsing is suppressed when $D < D_c$
- Energy limited by pump power only

Ding, Grelu, and Kutz, "Dissipative Soliton Resonance in a Passively Mode-Locked Fiber Laser," Opt. Lett. **36**, 1146 (2011)

2. Periodic Transmission

Ding, Shlizerman, and Kutz, "A Generalized Master Equation for High-Energy Passive Mode-Locking: the Sinusoidal Ginzburg-Landau Equation," IEEE J. Quantum Electron. **47**, 705 (2011)

Varying Saturable Absorber

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Nathan Kutz
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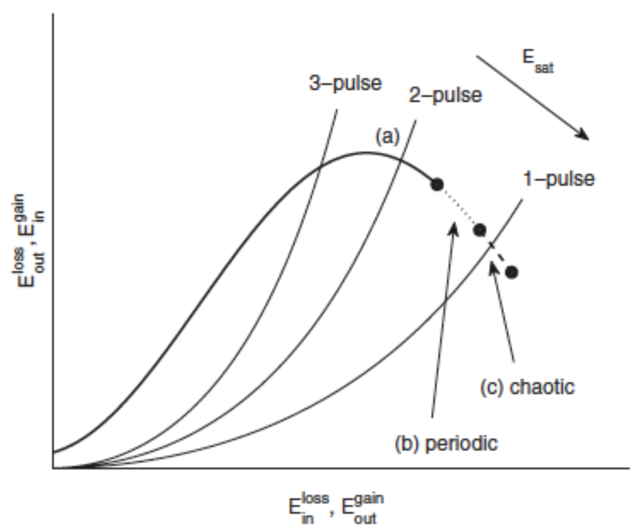
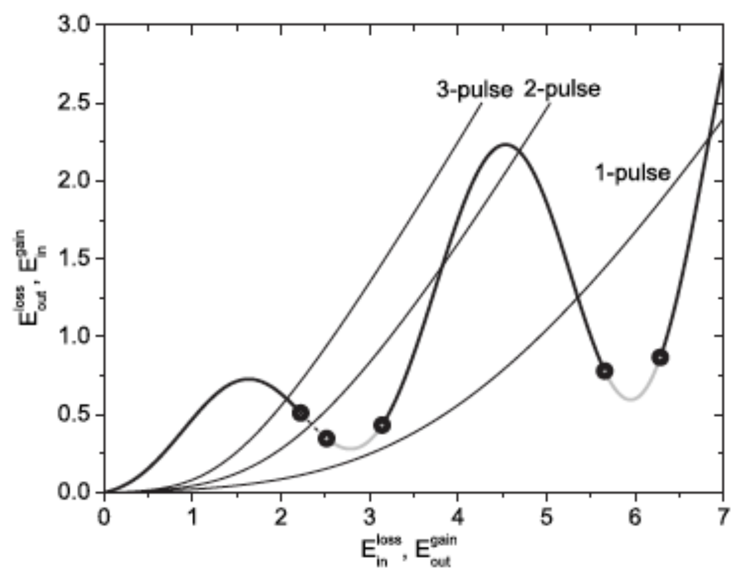
High-Energy Mode-Locking

- Artificial constraint in master mode-locking:

$$\beta > 0 > \mu$$ (Effective saturable absorption)

- Periodic transmission can yield high-energy pulses (Li *et al*, 2010)





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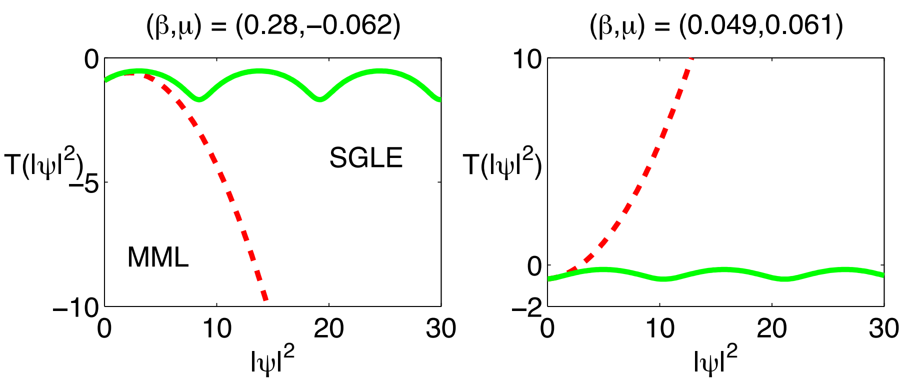
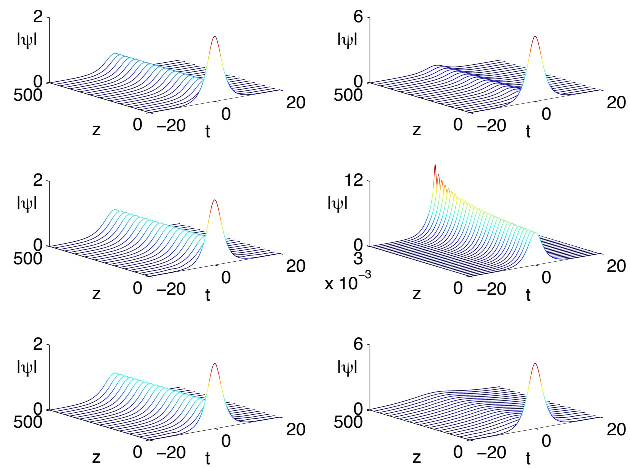
Li, Wai, and Kutz, "Geometrical description of the onset of the multi-pulsing in mode-locked laser cavities," J. Opt. Soc. Am. B **27**, 2068 (2010)

High-Energy Mode-Locking

- Sinusoidal Ginzburg-Landau Equation (SGLE)

$$i\psi_z + \frac{D}{2}\psi_{tt} + |\psi|^2\psi = ig(z)\left(1+\tau\partial_t^2\right)\psi - i\Gamma\psi + i(\log Q)\psi$$





Full

MML

SGLE

Better model than master mode-locking

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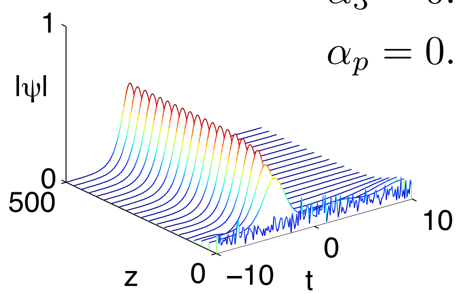
Ding, Shlizerman, and Kutz, "A Generalized Master Equation for High-Energy Passive Mode-Locking: the Sinusoidal Ginzburg-Landau Equation," IEEE J. Quantum Electron. **47**, 705 (2011)

High-Energy Mode-Locking

- SGLE captures high-energy pulses

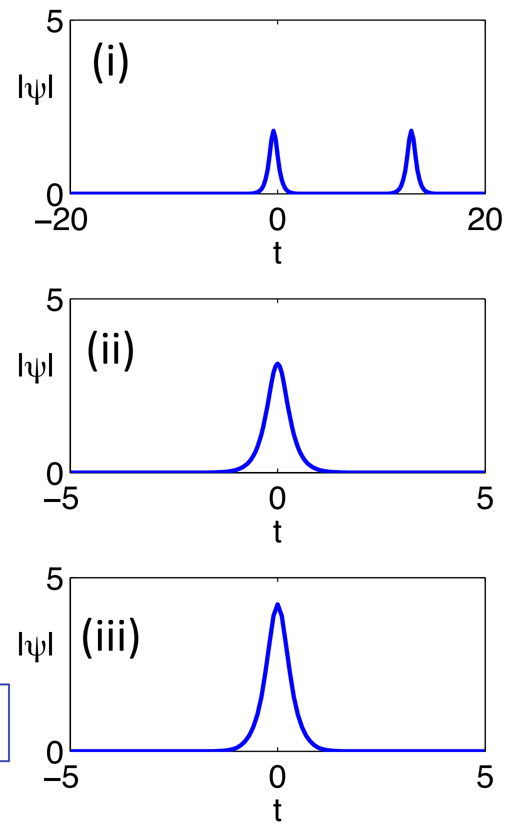
(i)
$$\alpha_1 = 0 \,, \quad \alpha_2 = 0.82\pi \,, \quad \alpha_3 = 0.1\pi \,, \quad \alpha_p = 0.45\pi \,.$$



(ii)
$$\alpha_1 = 0 \,, \quad \alpha_2 = 0.49\pi \,, \quad \alpha_3 = 0.2\pi \,, \quad \alpha_p = 0.45\pi \,.$$

(iii)
$$\alpha_1 = 0 \,, \quad \alpha_2 = 0.49\pi \,, \quad \alpha_3 = 0.25\pi \,, \quad \alpha_p = 0.45\pi \,.$$

Three-time increase in pulse energy



Double-pulse energy = 2.22

Single-pulse energy = 3

Single-pulse energy = 6.58
(MML fails)

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Ding, Shlizerman, and Kutz, "A Generalized Master Equation for High-Energy Passive Mode-Locking: the Sinusoidal Ginzburg-Landau Equation," IEEE J. Quantum Electron. **47**, 705 (2011)

Summary

- Multi-pulsing instability limits pulse energy
- High-energy pulses can be achieved by either the DSR or the periodic transmission

Future work

- Parameter Optimization
- Stability and bifurcations in the SGLE model