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Coupled photonics waveguides and cavities

Alessia Pasquazi

Dept. of Physics and Astronomy, University of Sussex, Brighton BN1 9QH UK

a.pasquazi@sussex.ac.uk

Outline

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The DNLSE in optics

- ***Array of waveguides-Spatial lattices***
  - ***purely nonlinear lattices***
- ***Synthetic optical lattices –temporal lattices***

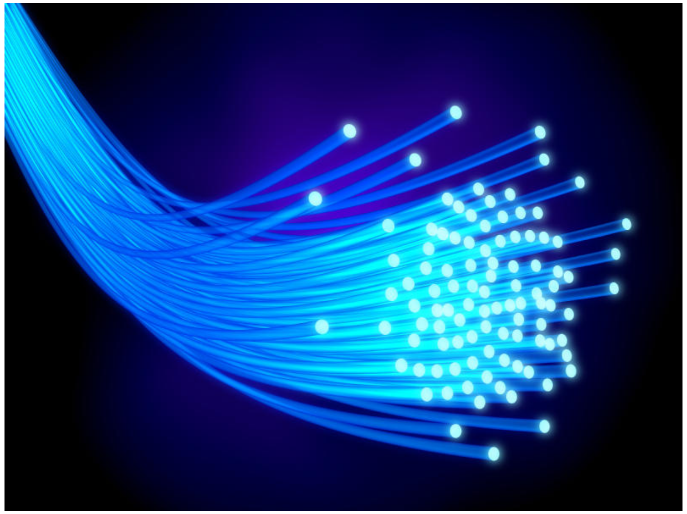
Optical microresonators and optical frequency combs

- ***Motivation***
- ***Low power and large bandwidth***
- ***The question of coherence***

Nested cavities approach

- ***Efficient modelling of the system***

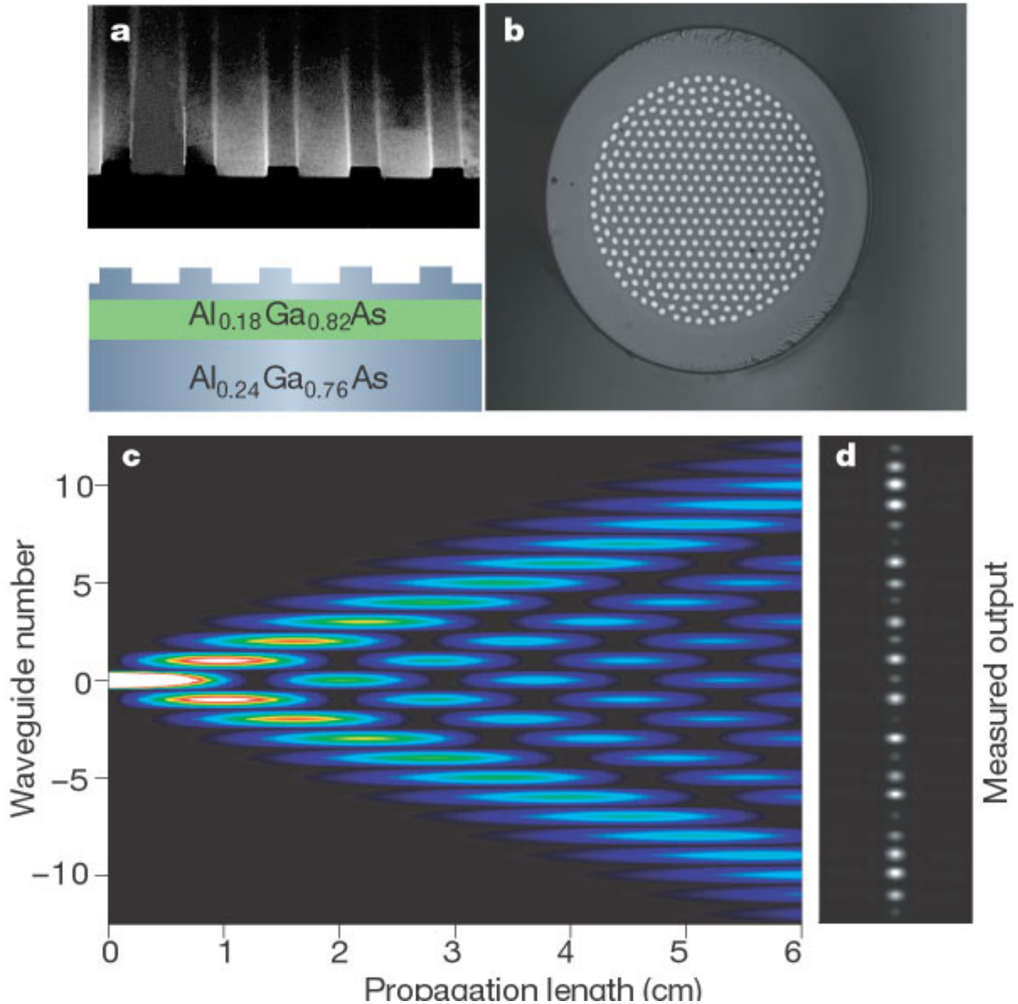
.. Recipe n 1 to build a DNLSE



1) Take a bunch of waveguides
2) Put them close
3) Add some power, nonlinearity is there
4) Watch the spatial propagation of the light

$$i\partial_z u_n(z) = k\, u_n(z) + \Gamma[u_{n+1}(z) + u_{n-1}(z)] + \gamma |u_n(z)|^2 u_n(z)$$

Discrete Array of Waveguides

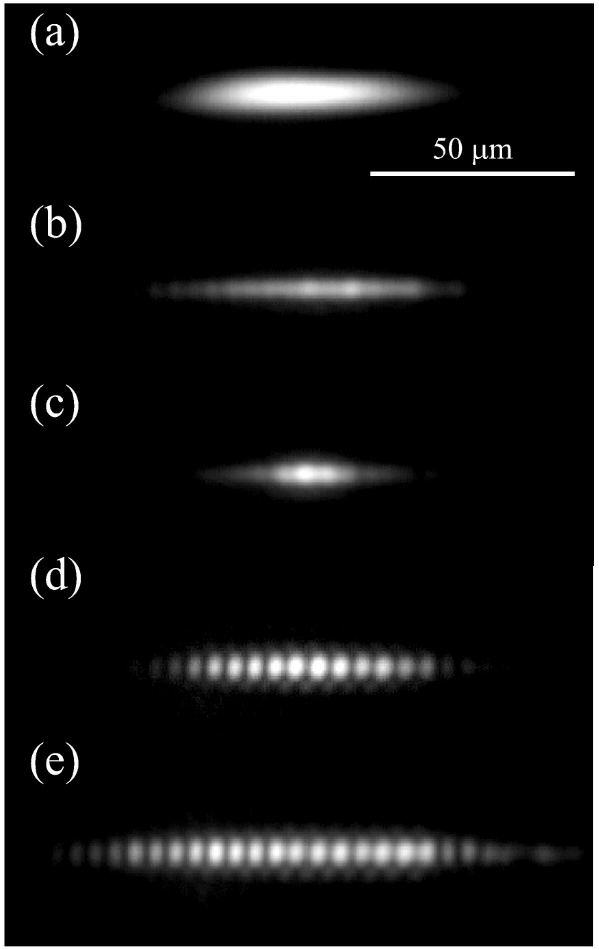


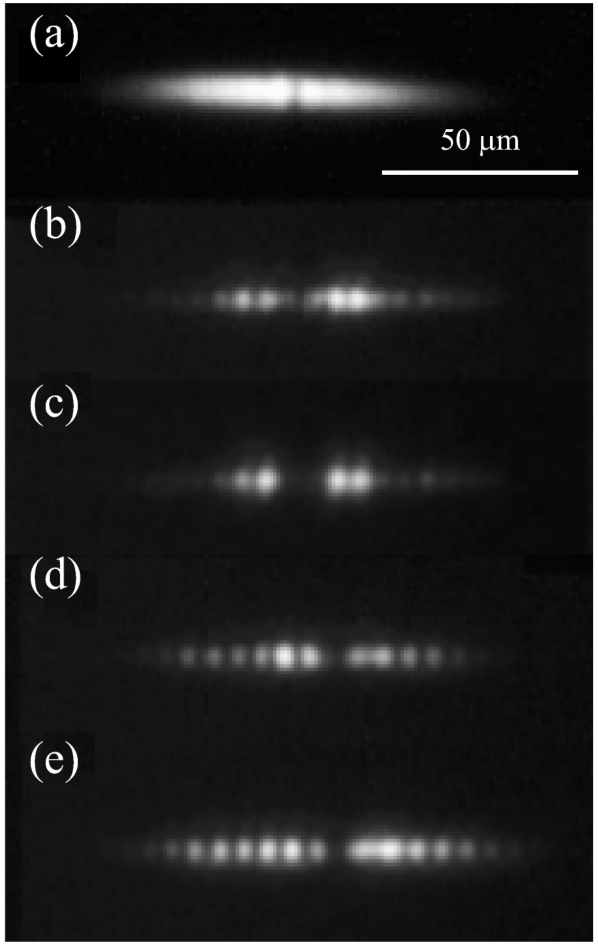
Aluminium gallium arsenide (AlGaAs) arrays (University of Glasgow, UK)

Silica glass (Institute for Physical High Technology Jena, Germany)

"Discrete solitons in optics" F. Lederer, G.I. Stegeman, D.N. Christodoulides, G Assanto, M. Segev and Y. Silberberg, Phys. Rep. 463, 1-126 (2008).
"Discretizing light behavious in linear and nonlinear waveguide lattices", D. Christodoulides, F. Lederer and Y. Silberberg, Nature, 424, 817 (2003).

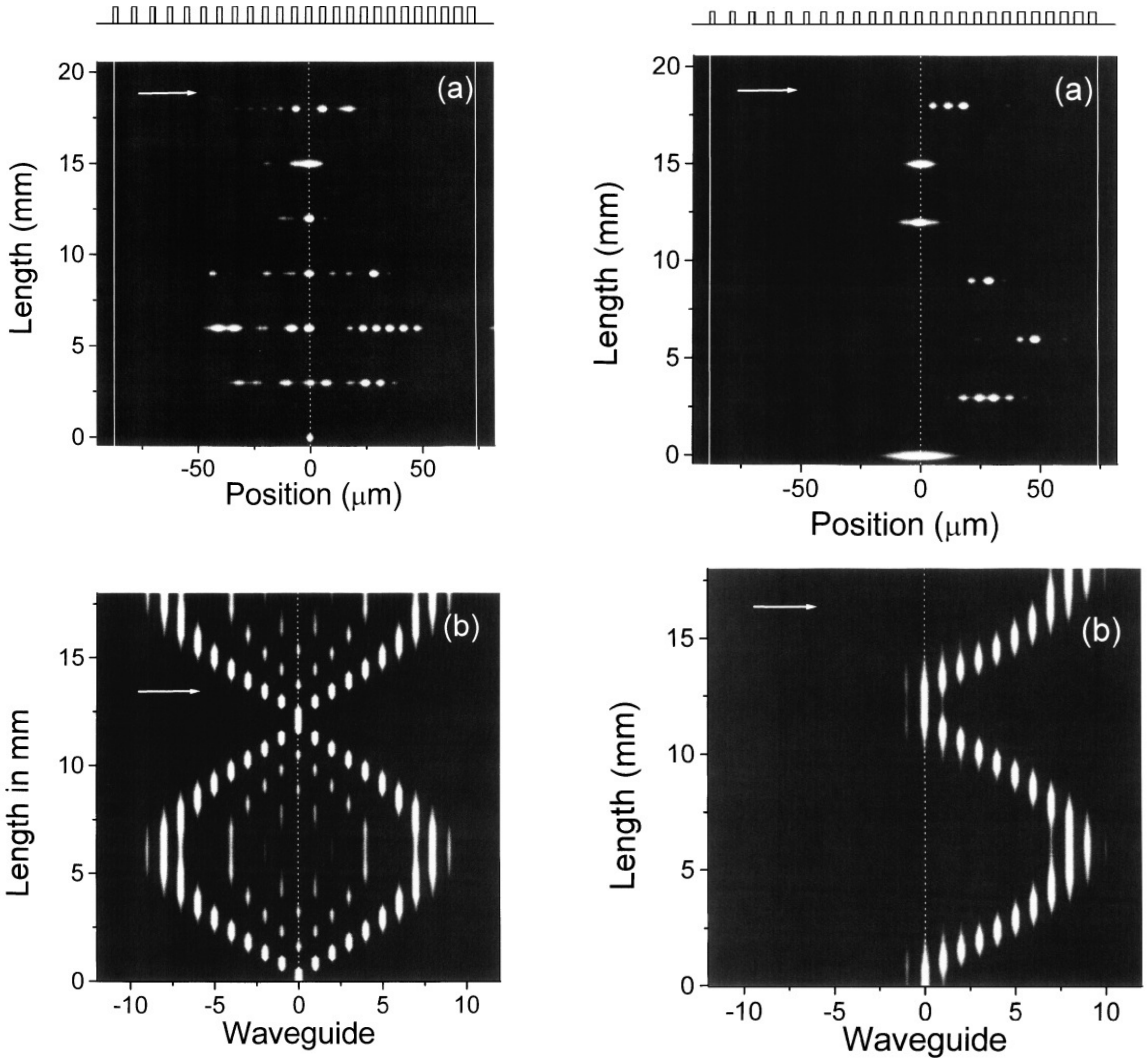
Bright and Dark Solitons





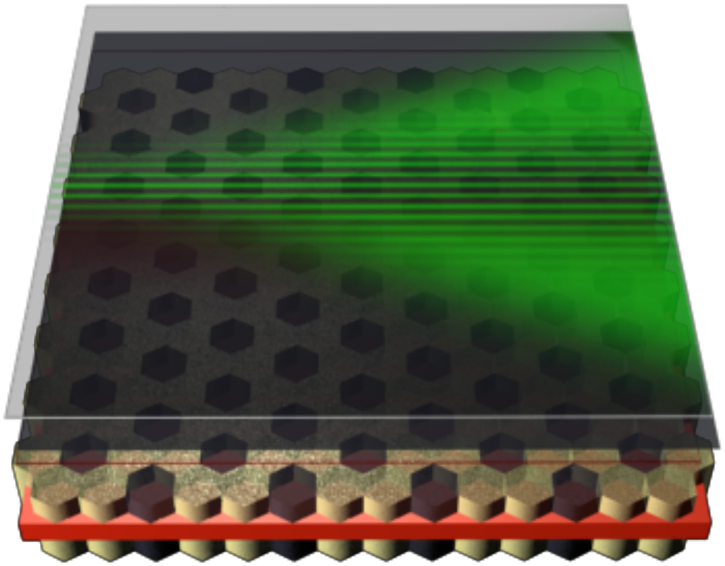
"Self-Focusing and Defocusing in Waveguide Arrays",
R. Morandotti, H. S. Eisenberg, Y. Silberberg, M. Sorel
and J. S. Aitchison, Phys. Rev. Lett. **86** , 3296 (2001).

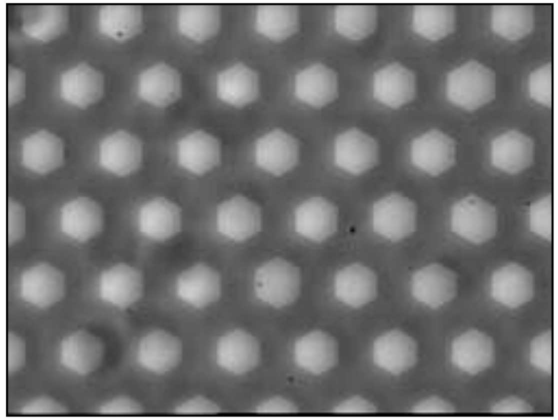
Bloch Oscillations

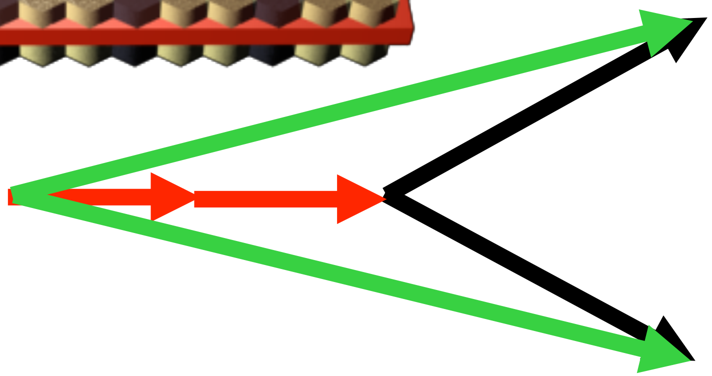


"Experimental Observation of Linear and Nonlinear Optical Bloch Oscillations" , R. Morandotti, U. Peschel, J.S. Aitchison, H. Eisenberg and Y. Silberberg, Phys. Rev. Lett., 83, 4756 (1999).

HexLN: a 2D nonlinear photonic lattice







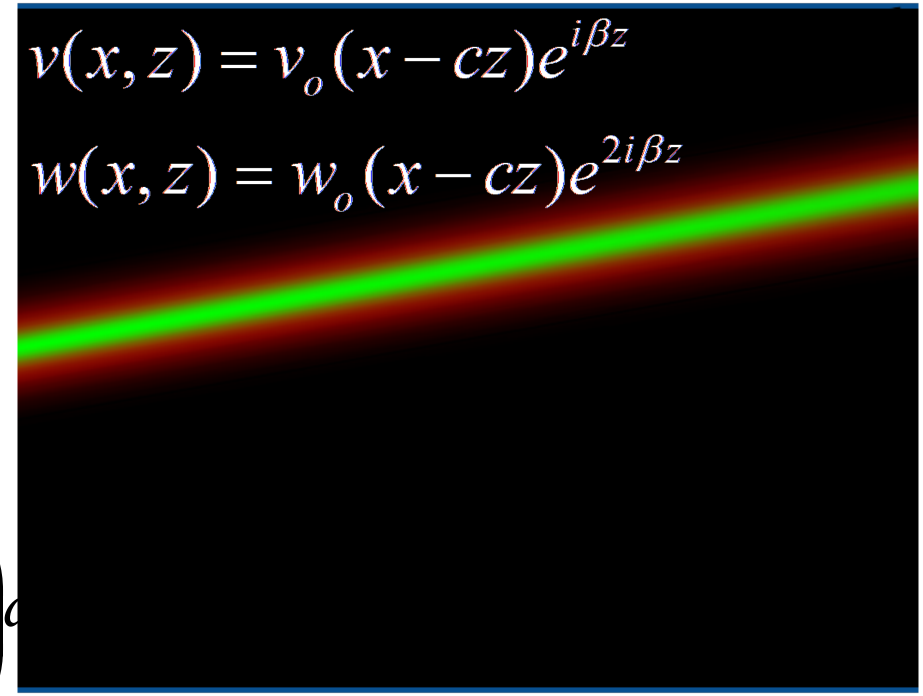
K. Gallo, A. Pasquazi, S. Stivala and G. Assanto, “Parametric Solitons in Two-Dimensional Lattices of Purely Nonlinear Origin”,Phys. Rev. Lett. 100, 053901 (2008).

A. Pasquazi and G. Assanto Quadratic solitons in degenerate quasi-phase-matched noncollinear geometry,Phys. Rev. A 80, 021801(R) – (2009)

Conserved quantities for QPM

$$i\partial_z v + \frac{1}{2}\partial_{xx} v + 2v^* w = 0$$

$$i\partial_z w + \frac{1}{4}\partial_{xx} w - \Delta w + 2v^2 = 0$$



Energy $$Q = \int\left(|v|^2 + |w|^2\right)dx$$

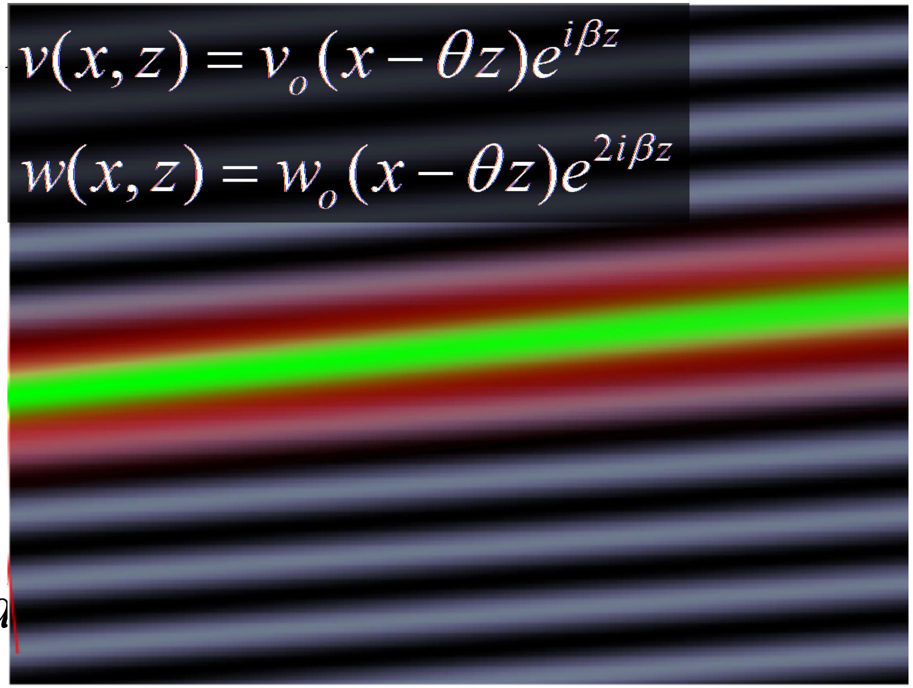
Momentum $$M = i\int \mathrm{Im}\left(vv_x^* + \frac{ww_x^*}{2}\right)d$$

Hamiltonian $$H = \int\left(\frac{|v_x|^2}{2} + \frac{|w_x|^2}{8}\right)dx - \frac{\Delta}{2}Q_w - 2\int \mathrm{Re}\left(v^2 w^*\right)dx$$

Conserved quantities for DQPM

$$i\partial_z v + \frac{1}{2}\partial_{xx} v + 2\cos[\gamma(x-\theta z)]v^*$$

$$i\partial_z w + \frac{1}{4}\partial_{xx} w - \Delta w + 2\cos[\gamma(x-$$

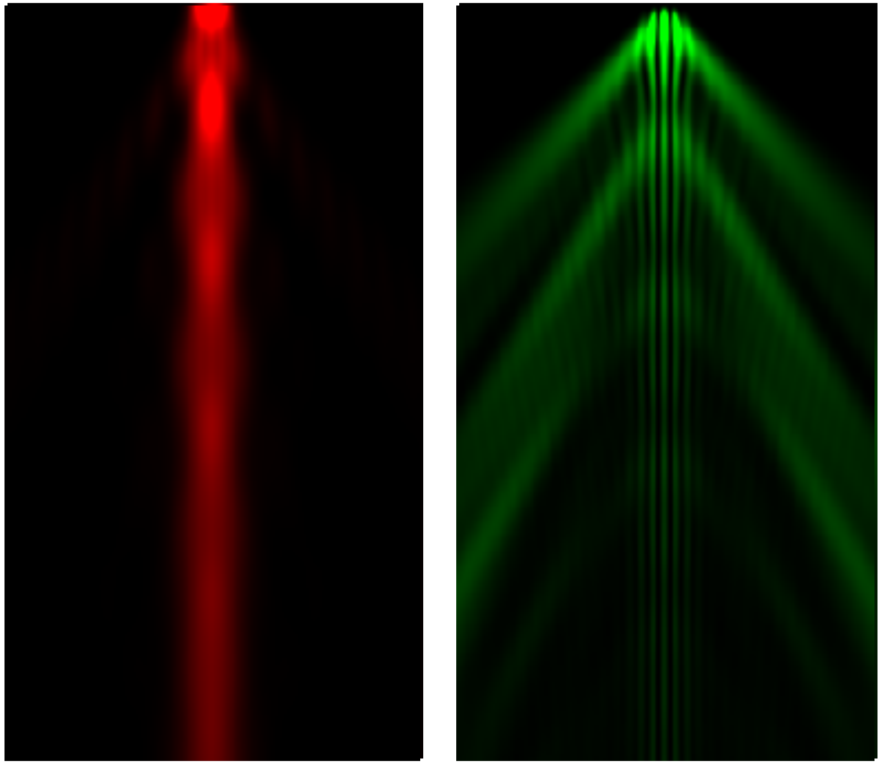


Energy $$Q = \int\left(|v|^2 + |w|^2\right)dx$$

Momentum $$M = i\int \mathrm{Im}\left(vv_x^* + \frac{ww_x^*}{2}\right)d$$

Hamiltonian $$H = \int\left(\frac{|v_x|^2}{2} + \frac{|w_x|^2}{8}\right)dx - \frac{\Delta}{2}Q_w - 2\int \cos[\gamma(x-\theta z)\,\mathrm{Re}\left(v^2 w^*\right)dx$$

Degenerate QPM: a new class of solitary waves



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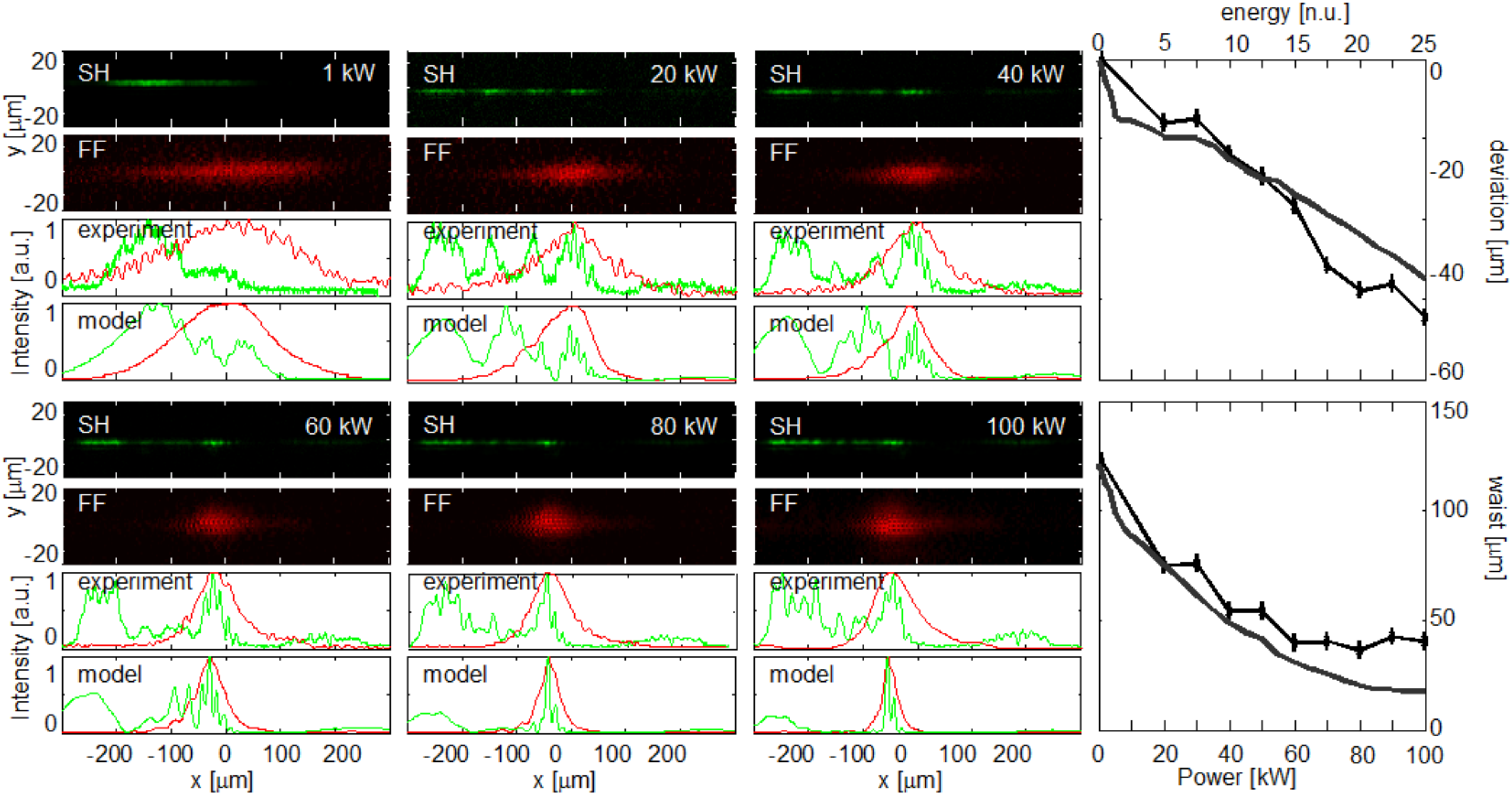
Degenerate QPM: a new class of solitary waves



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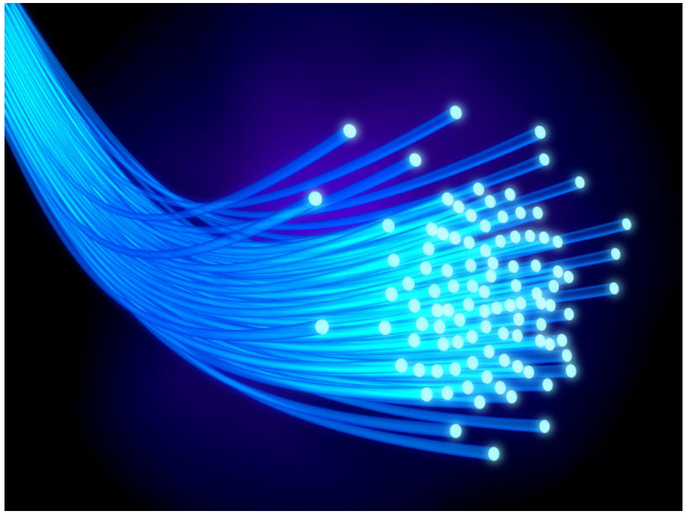
A. Pasquazi and G. Assanto Quadratic solitons in degenerate quasi-phase-matched noncollinear geometry,Phys. Rev. A 80, 021801(R) – (2009)

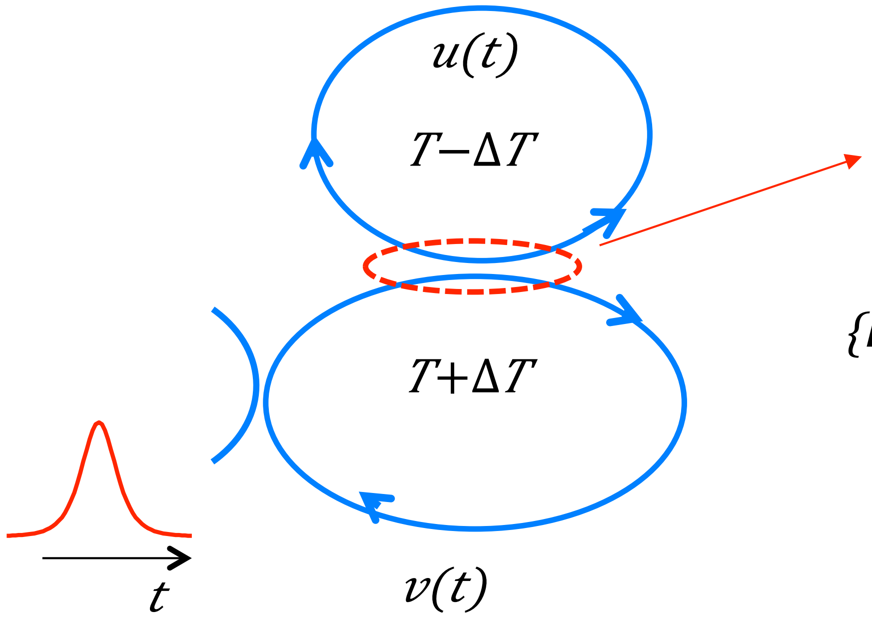
.. Recipe n 2 to build a D(N)LSE



1) Take 2 waveguides
2) Put them close
3) Close them in a loop
4) Watch the propagation of a pulse

$$u_n^{m+1} - u_n^{m-1} = i\sqrt{2}\,[u_{n+1}^{m} + u_{n-1}^{m}]$$
$$2\partial_m u_n = i\sqrt{2}\,[u_{n+1} + u_{n-1}]$$

Synthetic Photonic Lattices



$$\{ u_{out}(t)=1/\sqrt{2}\ [i\,u_{in}(t)+\ v_{in}(t)] \,@\, v_{out}$$

$$\{ u(t)=1/\sqrt{2}\ [i\,u(t-T+\Delta T)+\ v(t-T-\Delta T)] \,@\, v(t)=$$

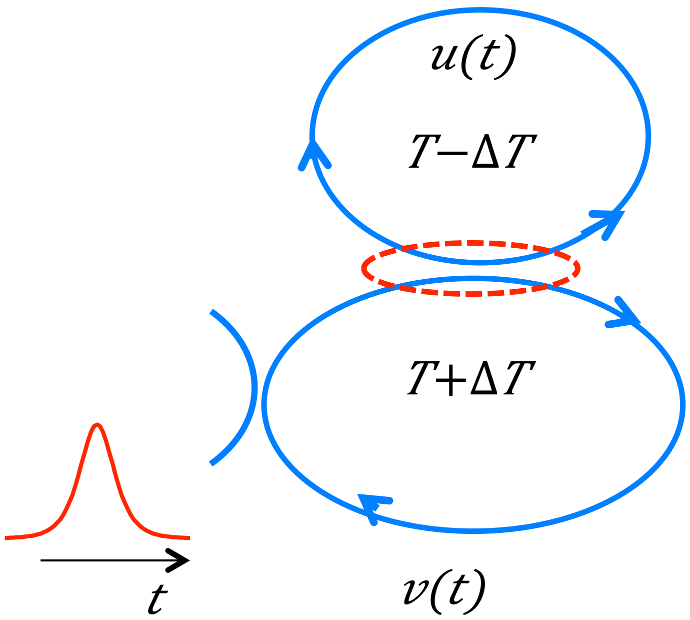
$$v(t)=\sum_m \sum_{n=1}^{N} v_n^m\,(t-mT+n\,\Delta T-2\Delta T) \qquad u(t)=\sum_m \sum_{n=1}^{N} u_n^m\,(t-m$$

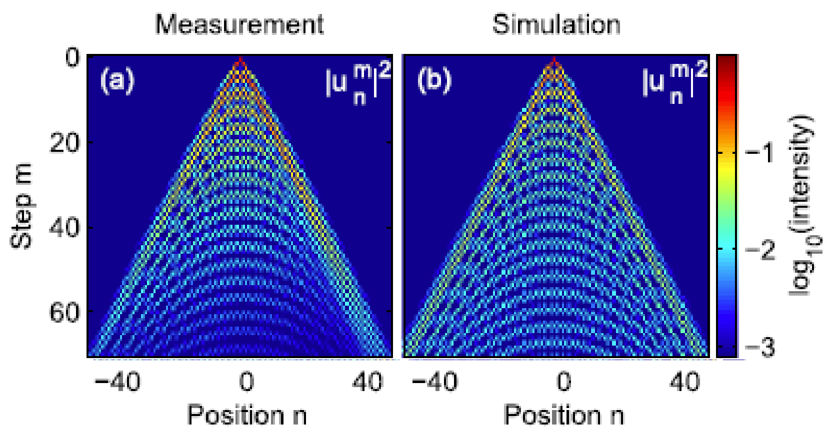
$$\{ u_n^{m+1}\,(t)=1/\sqrt{2}\ [i\,u_{n+1}^m+\ v_{n+1}^m\,] \,@\, v_n^{m+1}\,(t)=1/\sqrt{2}\ [u_{n-1}^m+i\,v$$

$$u_n^{m+1}-u_n^{m-1}=i\sqrt{2}\ [u_{n+1}^m+u$$

Schreiber, A. *et al.* Photons walking the line: a quantum walk with adjustable coin operations. Phys. Rev. Lett. 104, 050502 (2010)
Regensburger, A. *et al.* Photon propagation in a discrete fiber network: an interplay of coherence and losses. Phys. Rev. Lett. 107, 233902 (2011)

Synthetic Photonic Lattices





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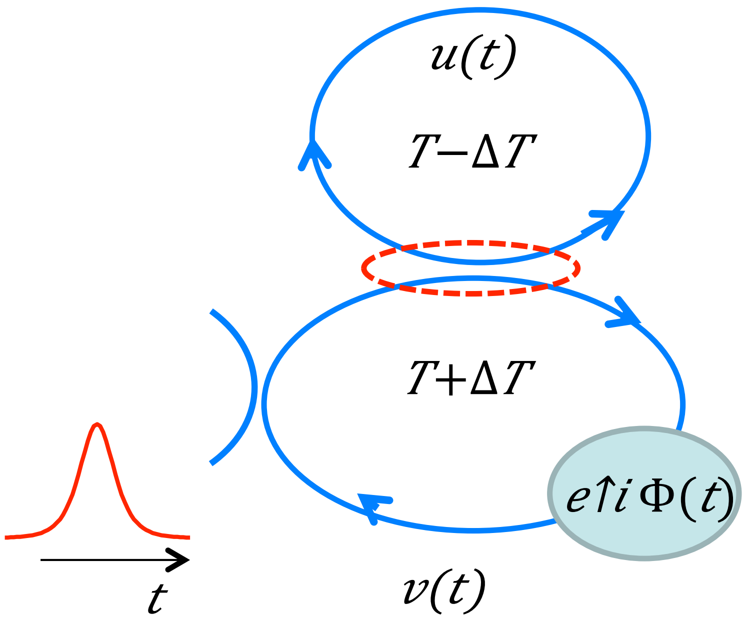
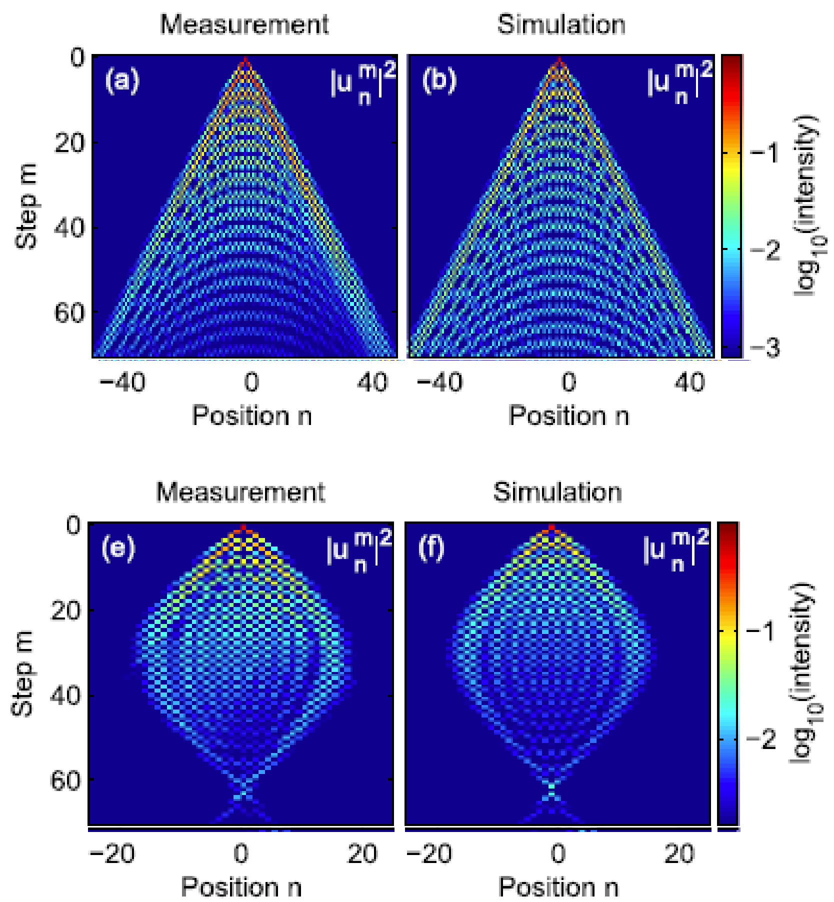
Regensburger, Bersch, Miri, Onishchukov, Christodoulides & Peschel, Parity–time synthetic photonic lattices, Nature 488,167–171 (2012)

Synthetic Photonic Lattices





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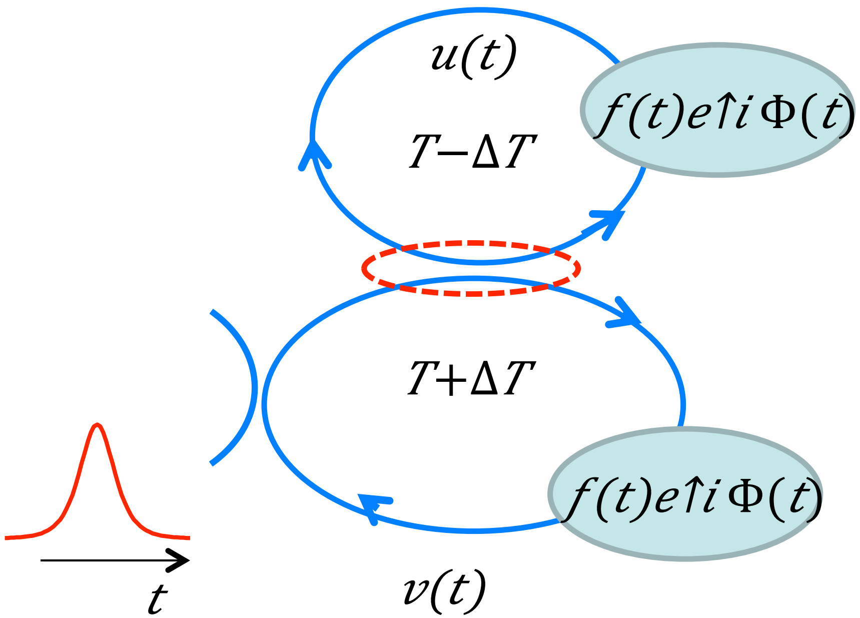
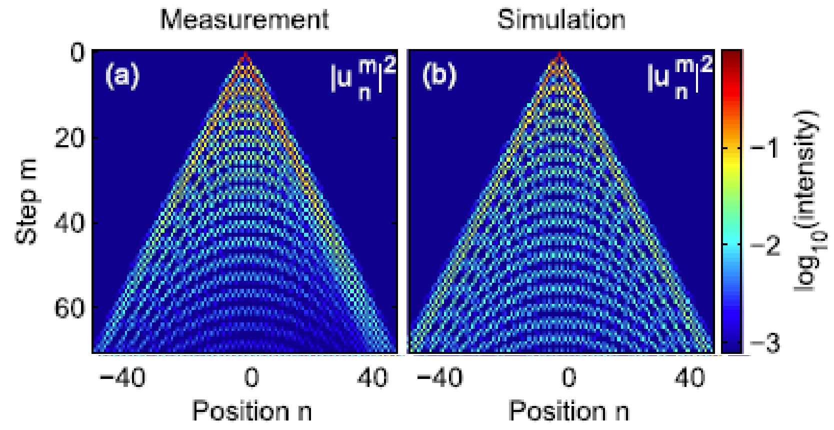
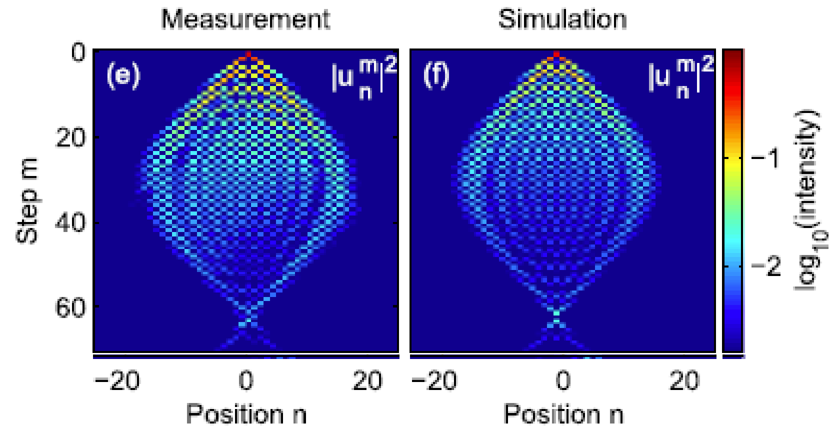
Synthetic Photonic Lattices







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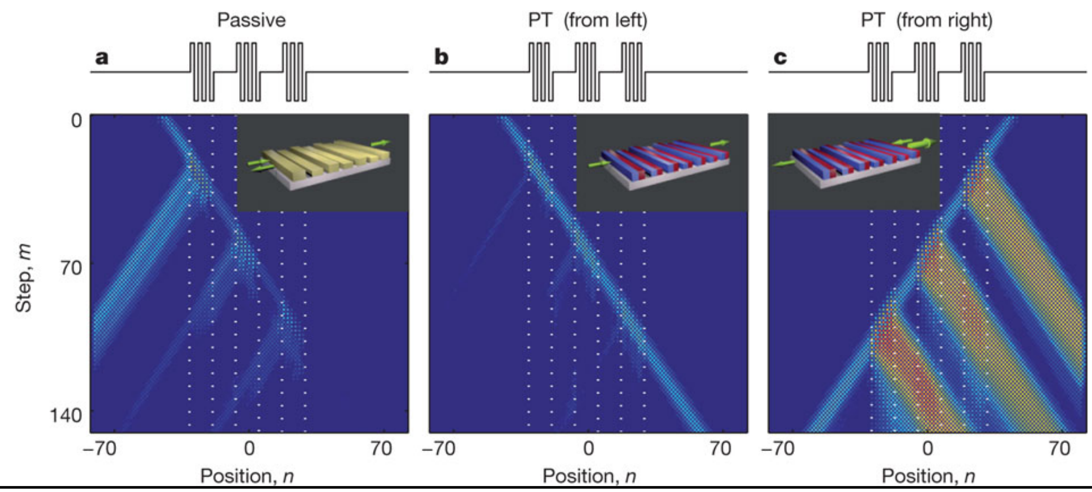

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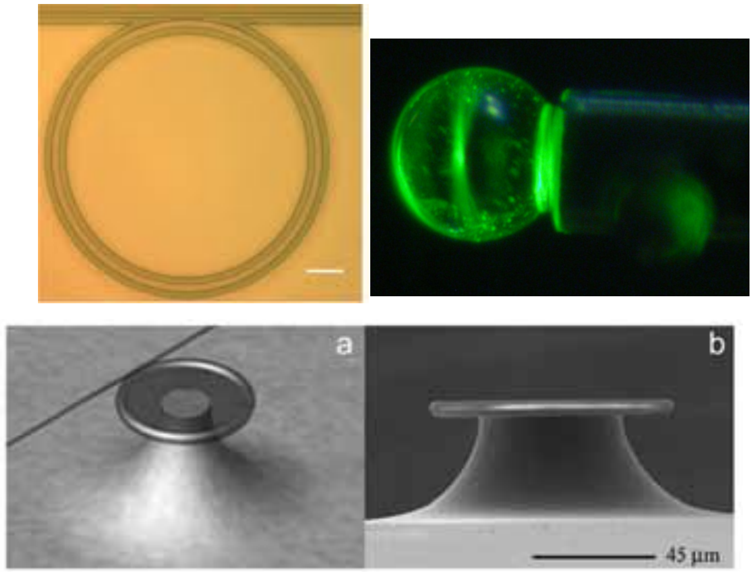
On-*Ch*ip *R*esonating *O*ptical Systems via *N*onlinear *O*ptics (CHRONOS)

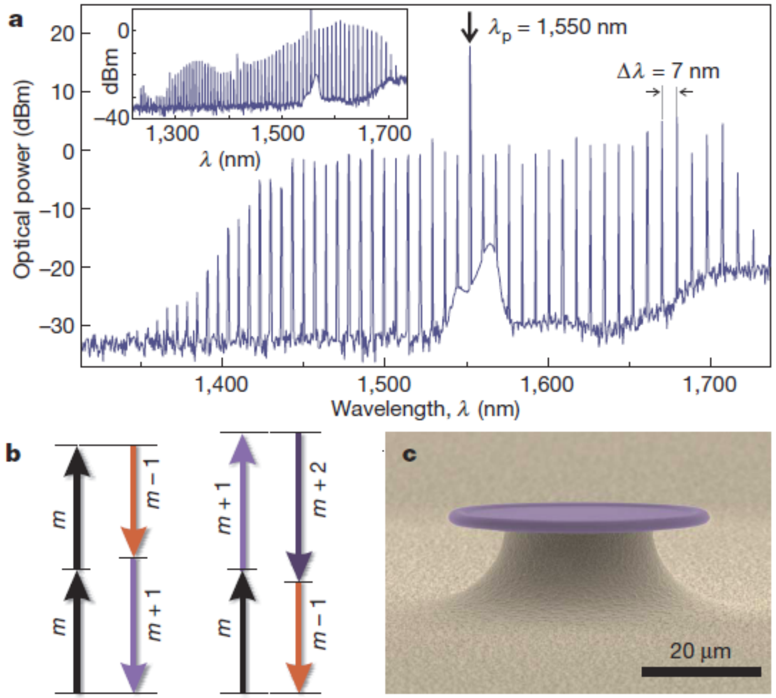
- Why Microcavities?
  - State of the art optical components
  - Already on the market (e.g. sensors)
  - Can be integrated (one of the few optical technology ready for CMOS large areas fabrication)
  - NONLINEAR WITH LOW ENERGY



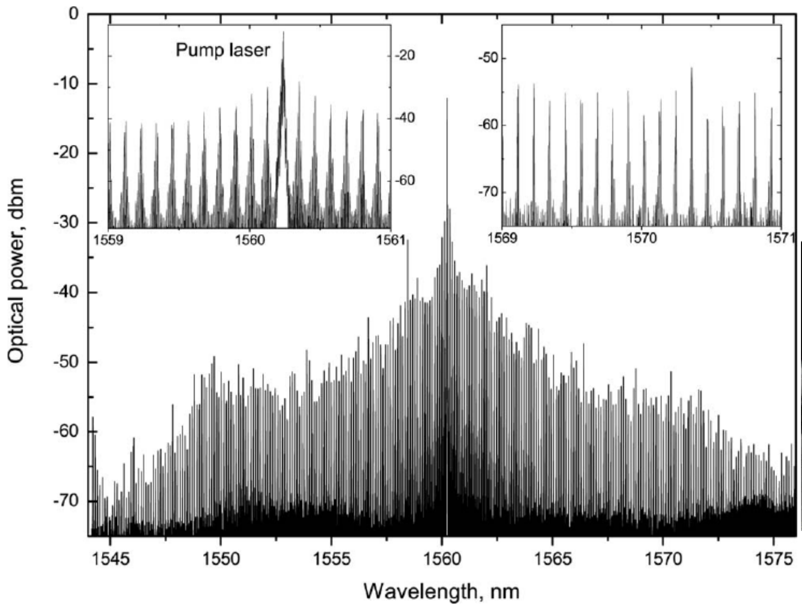
Towards Compact High Rep-Rate Sources

OPO in High-Q resonator
as Ultrafast sources

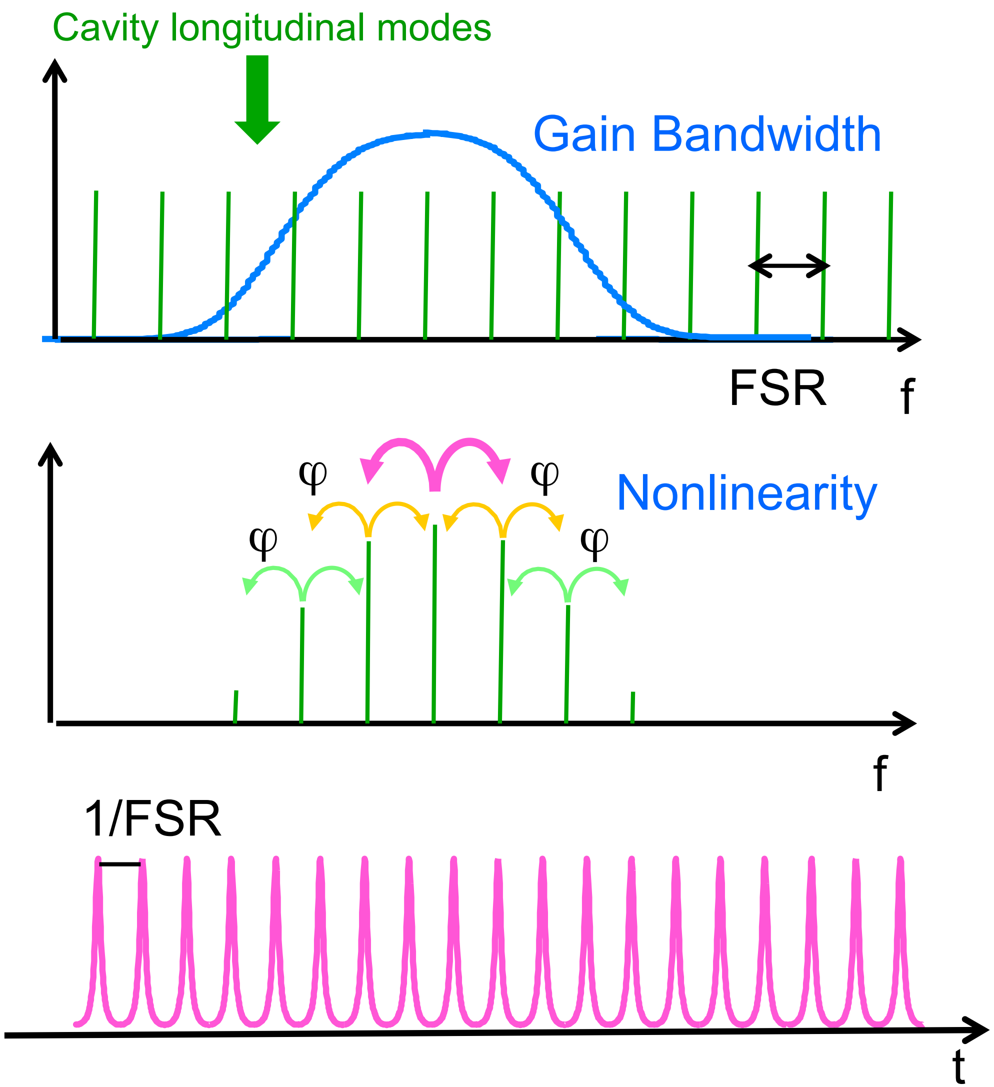
P. DelHaye et al. Nature 450, 1214–1217 (2007). FSR=870GHz

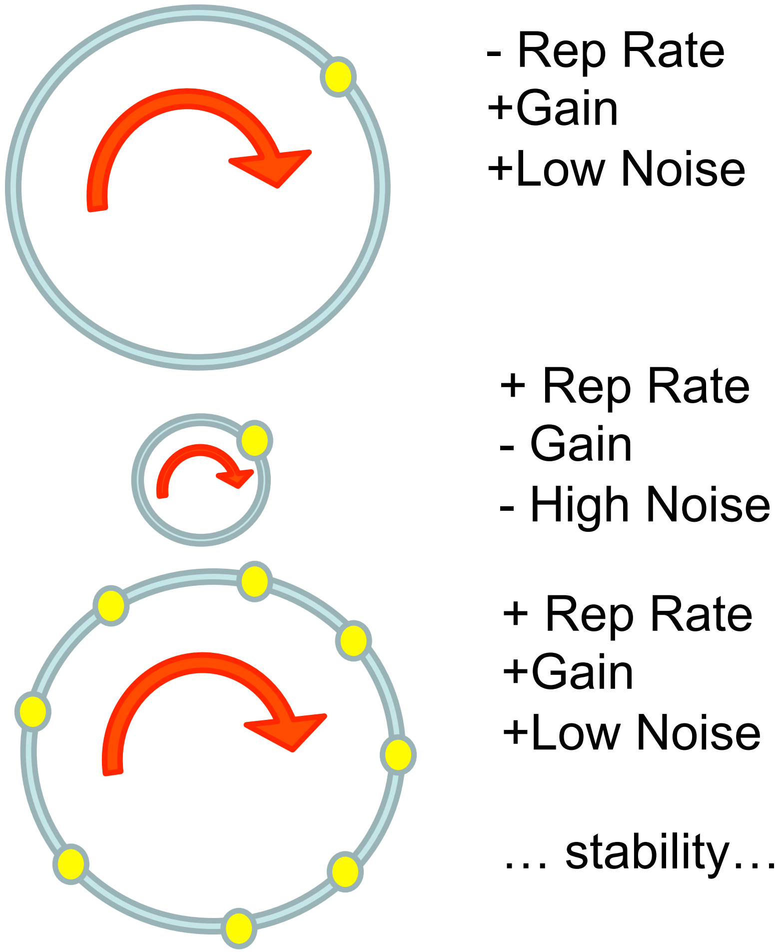


I. S. Grudinin, et al. Opt. Lett. 34, 878–880 (2009).



Laser and Mode-Locking





P. Grelu and N. Akhmediev, "Dissipative solitons for mode-locked lasers," Nat. Photonics 6, 84–92 (2012).

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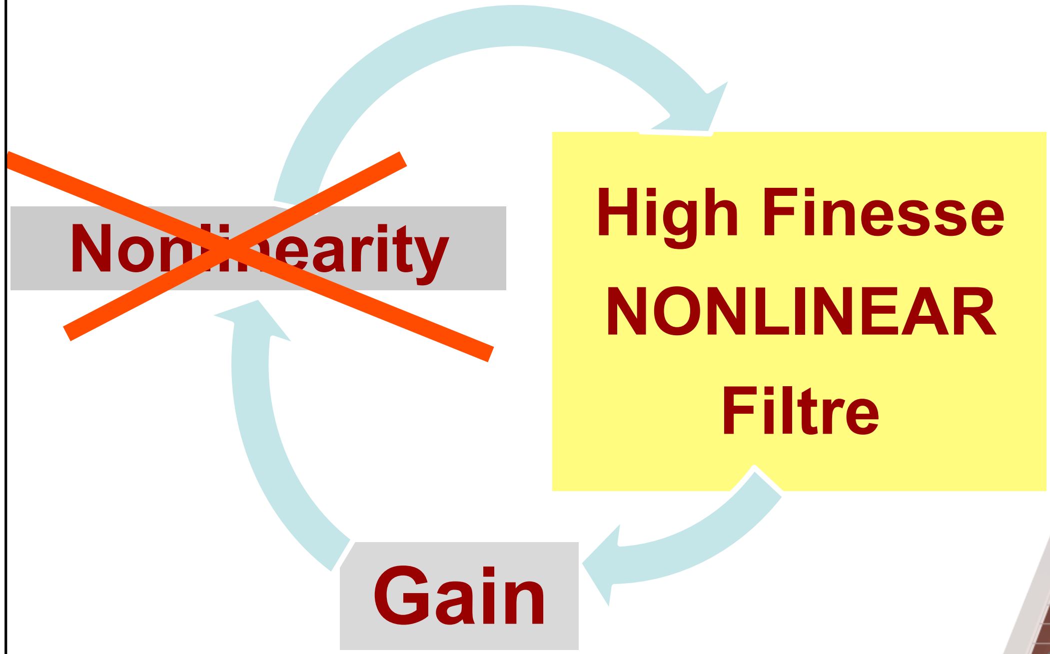
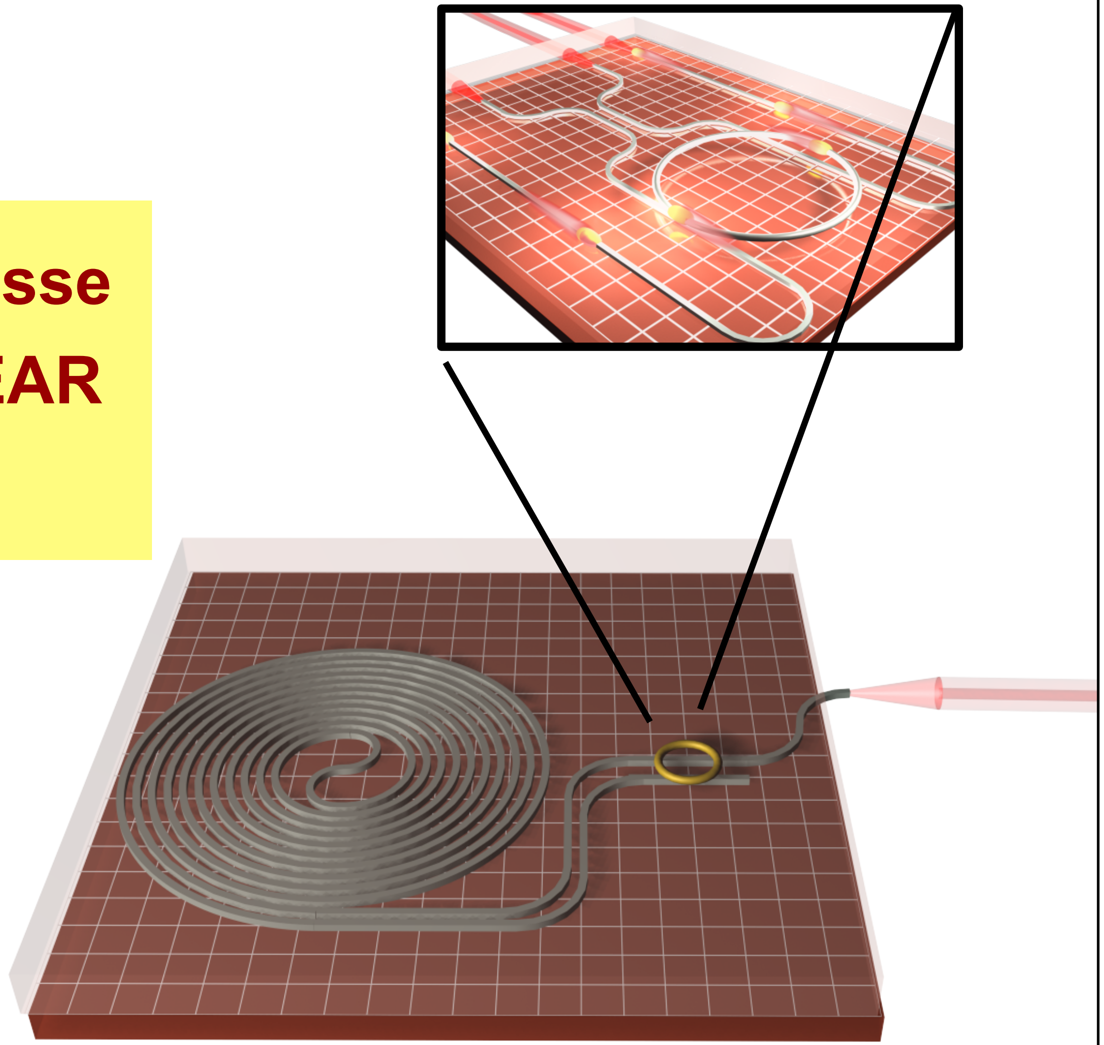
OPEN

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]

Nature Communications ***3***, *765 (2012)*

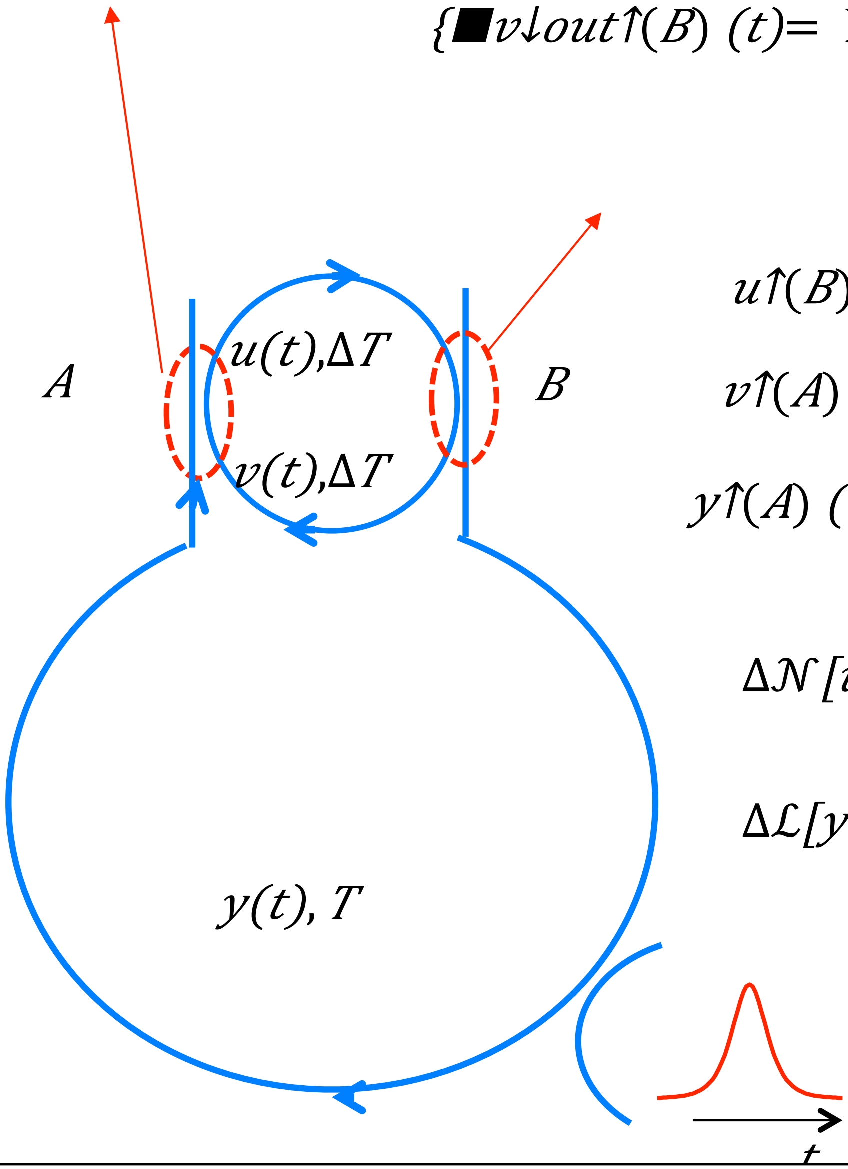




Synthetic Photonic Lattices

$u_{out}^{(A)}(t)=\Gamma e^{i\Phi_v} v_{in}^{(A)}(t)+i K e^{i\Phi_y} y_{in}^{(A)}(t)$ $\Gamma^2+K^2=1$

$\{ v_{out}^{(B)}(t)= \Gamma e^{i\Phi_u} u_{in}^{(B)}(t) \; @ \; y_{out}^{(B)}(t)=-i K e^{i\Phi_u} u$



$u^{(B)}(t+\Delta T)= \mathcal{N}[u^{(A)}(t)] \approx u^{(A)}(t)+\Delta\mathcal{N}[u^{(A)}(t)$

$v^{(A)}(t+\Delta T)= \mathcal{N}[v^{(B)}(t)] \approx v^{(B)}(t)+\Delta\mathcal{N}[v^{(B)}(t)]$

$y^{(A)}(t+T)= \mathcal{L}[y^{(B)}(t)] \approx y^{(B)}(t)+\Delta\mathcal{L}[y^{(B)}(t)]$

$\Delta\mathcal{N}[u(t)]=i\Delta Z[-1/2\, \beta\, \partial_{tt} u(t)+\gamma |u(t)|^2 u(t)]$

$\Delta\mathcal{L}[y(t)]=i\Delta L[-1/2\, \beta\, \partial_{tt} y(t)+ig\, y(t)]$

Synthetic Photonic Lattices

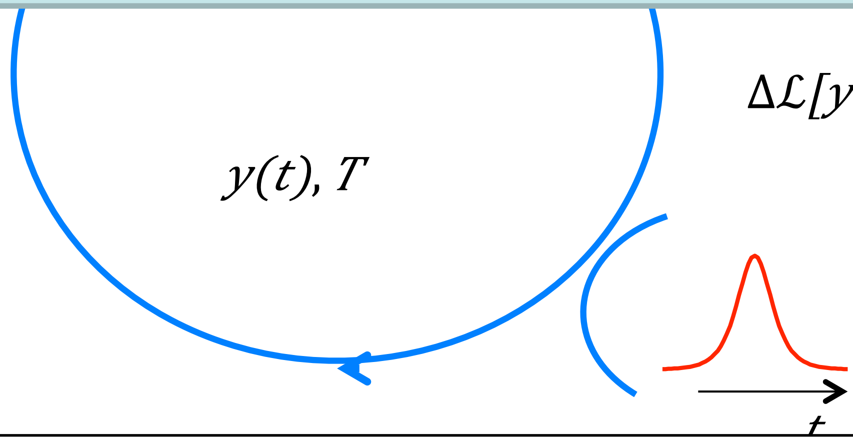
$u_{out}^{(A)}(t)=\Gamma e^{i\Phi_v} v_{in}^{(A)}(t)+i K e^{i\Phi_y} y_{in}^{(A)}(t)$ $\Gamma^2+K^2=1$

$\begin{cases} v_{out}^{(B)}(t)=\Gamma e^{i\Phi_u} u_{in}^{(B)}(t) \\ y_{out}^{(B)}(t)=-i K e^{i\Phi_u} u \end{cases}$

$\mathcal{N}^{-1}[u_{n+1}^{m}(t)]e^{-i\Phi_u}-\Gamma e^{i\Phi_v}\mathcal{N}[\Gamma u_{n}^{m}(t)]=K^2 \mathcal{L}[u_{n}^{m-1}(t)]e^{i\Phi_y}$

$u_{n+1}^{m}(t)e^{-i\Phi_u}-\Gamma^2 u_{n}^{m}(t)e^{i\Phi_v}-K^2 u_{n}^{m-1}(t)e^{i\Phi_y}=$

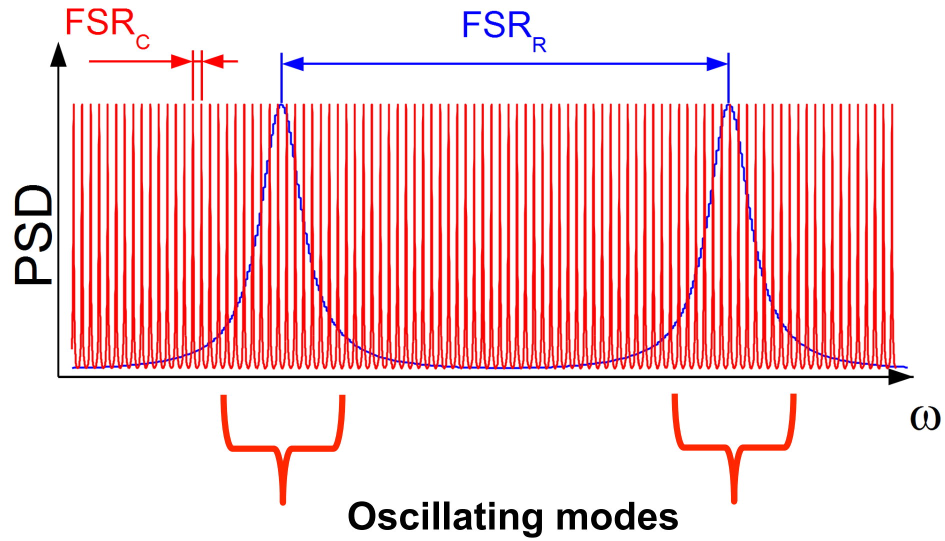
$\Delta\mathcal{N}[u_{n+1}^{m}(t)]e^{-i\Phi_u}+\Gamma e^{i\Phi_v}\Delta\mathcal{N}[\Gamma u_{n}^{m}(t)]+K^2\Delta\mathcal{L}[u_{n}^{m-1}(t)]e^{i\Phi_y}$

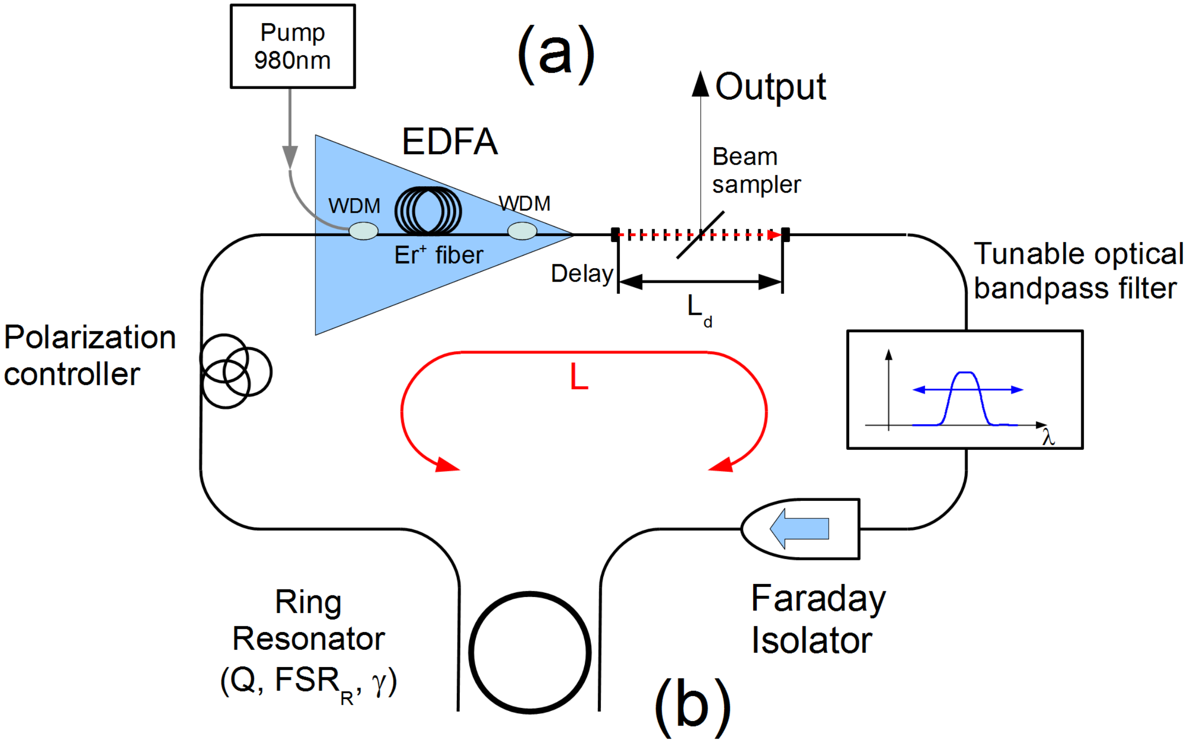


$\Delta\mathcal{L}[y(t)]=i\Delta L[-1/2\,\beta\,\partial_{tt}\,y(t)+ig\,y(t)]$

Laser setup

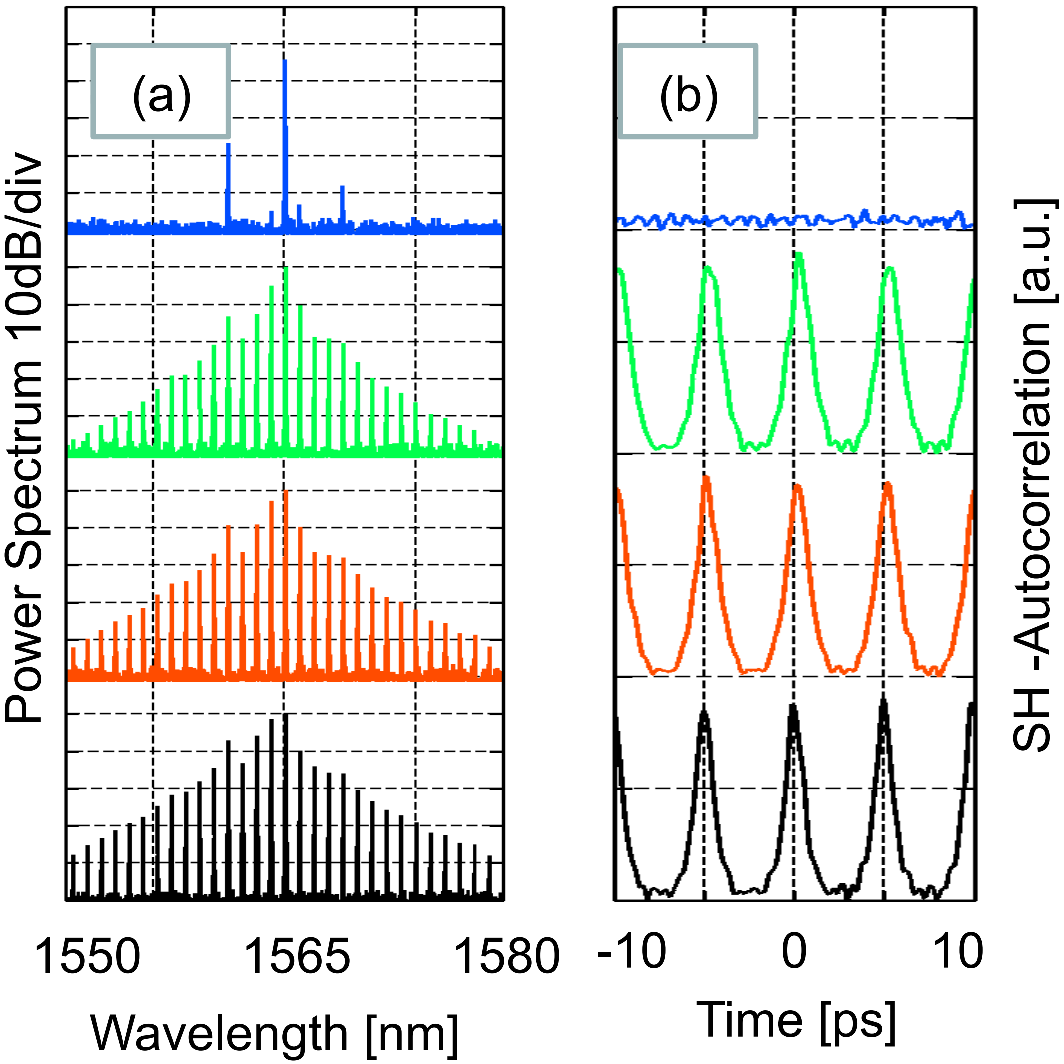
Multiple-mode per resonance oscillation



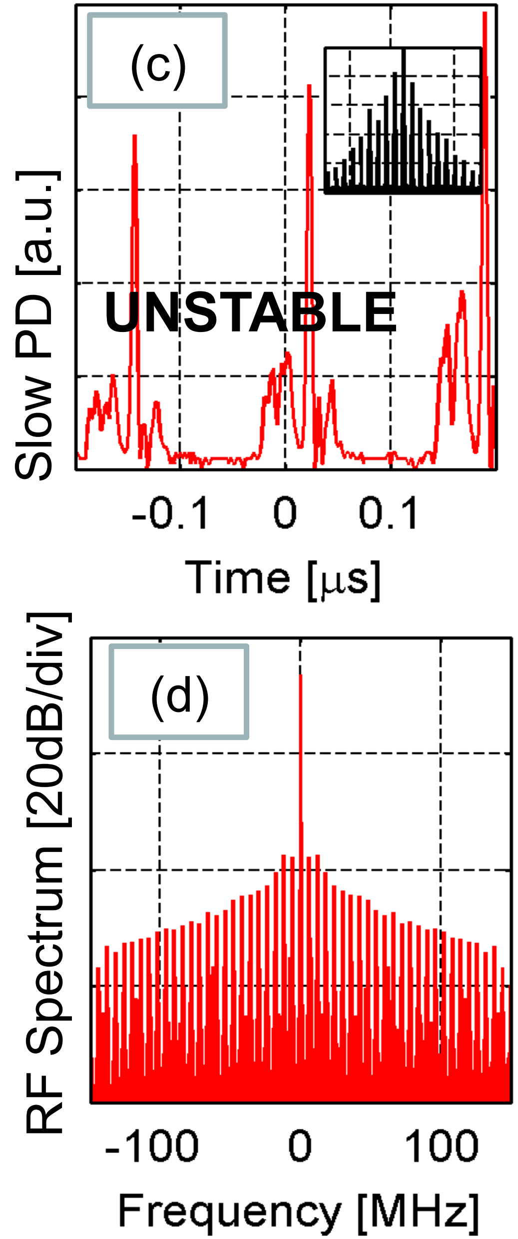


Long main cavity: many modes per ring resonance

The main cavity has FSR=6MHz (33 meter of SMF).
Gain 33dB saturation power 3W



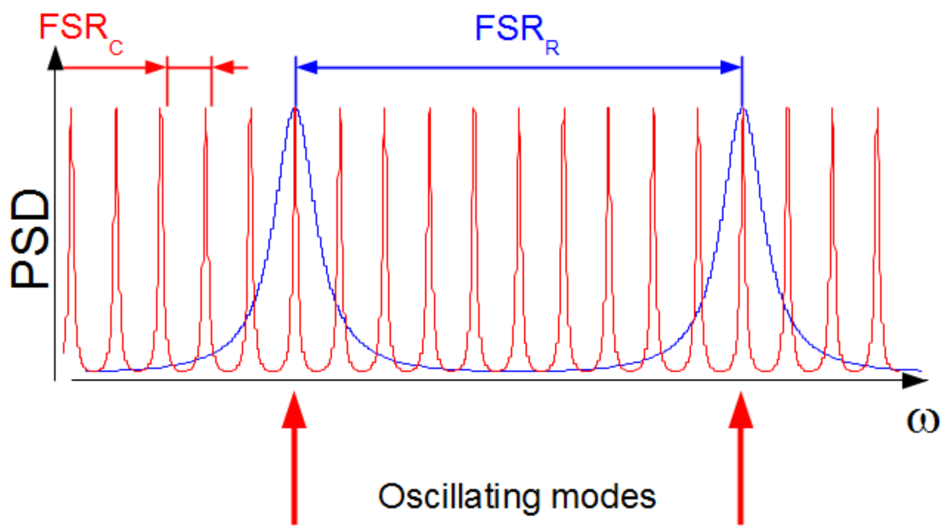
Max power in the Ring 60mW

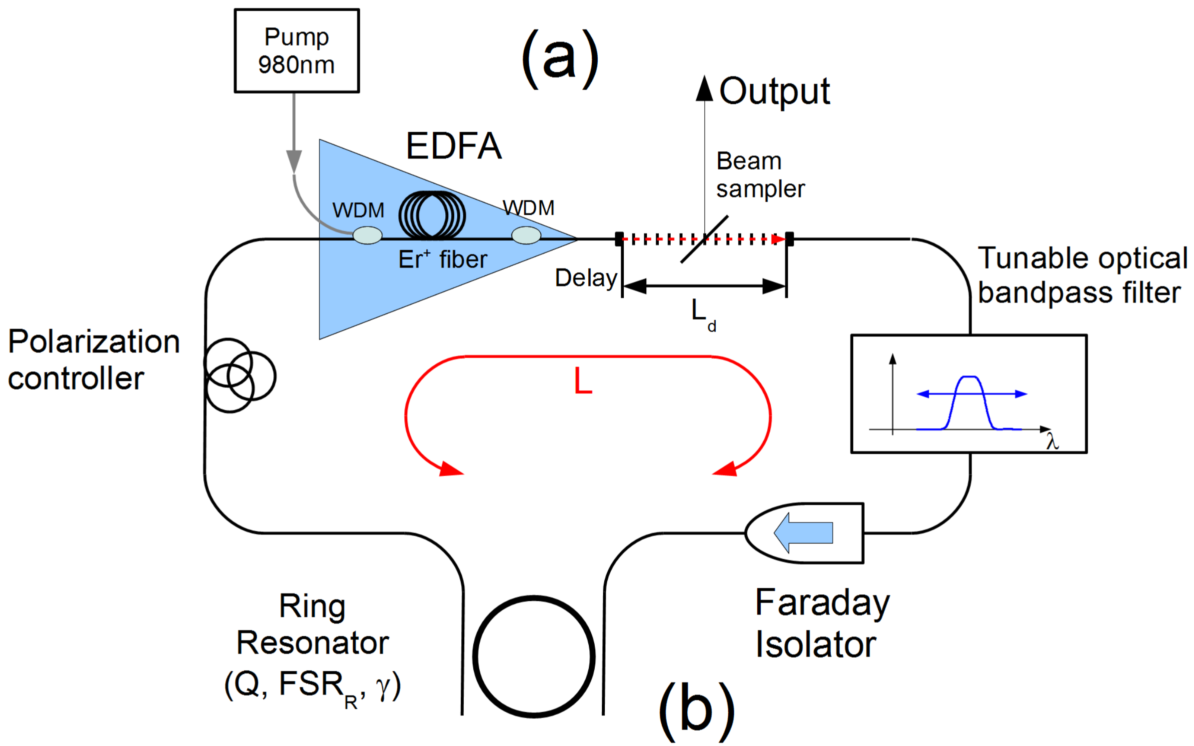


M. Peccianti at al., Nature Communications ***3****, 765 (2012)*

Laser setup

Single-mode per resonance oscillation

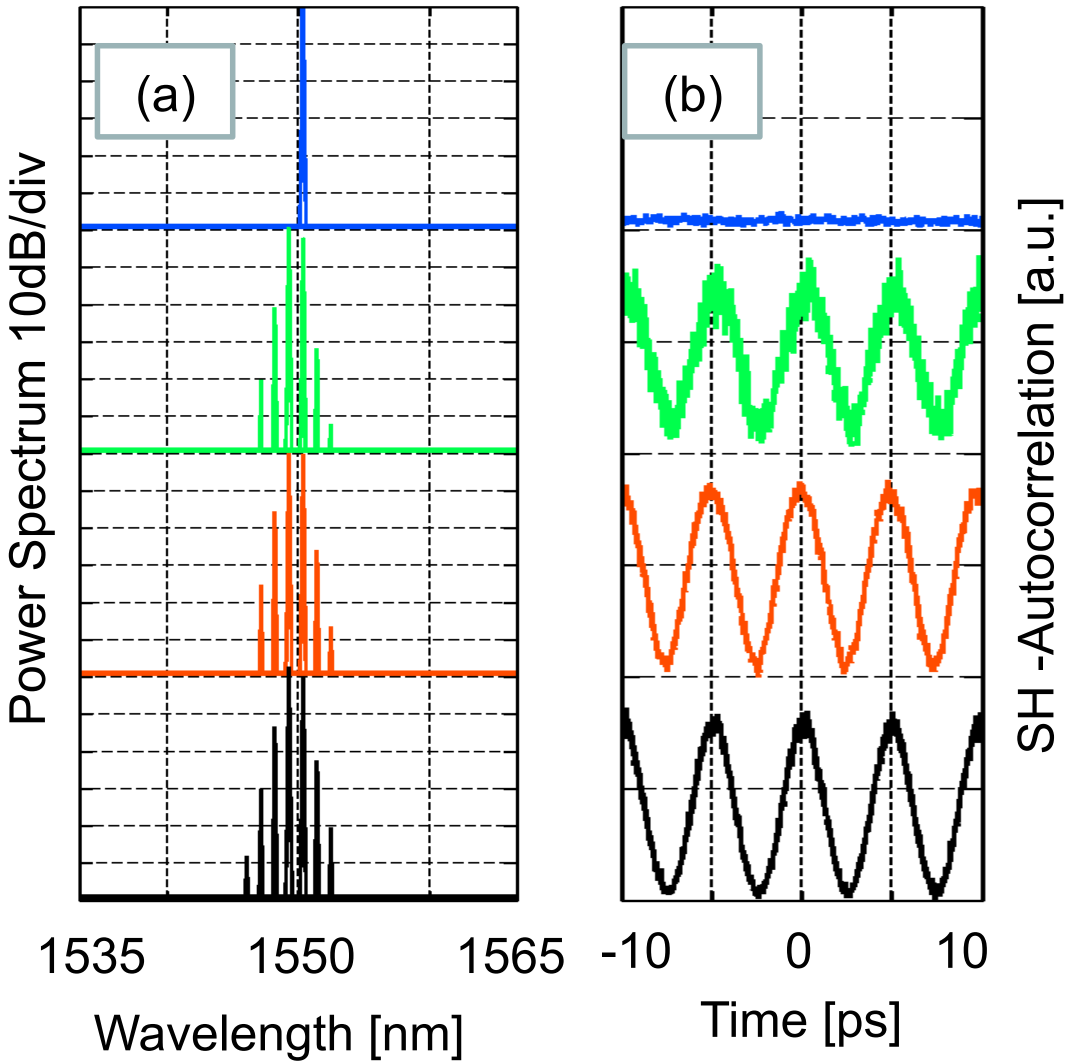




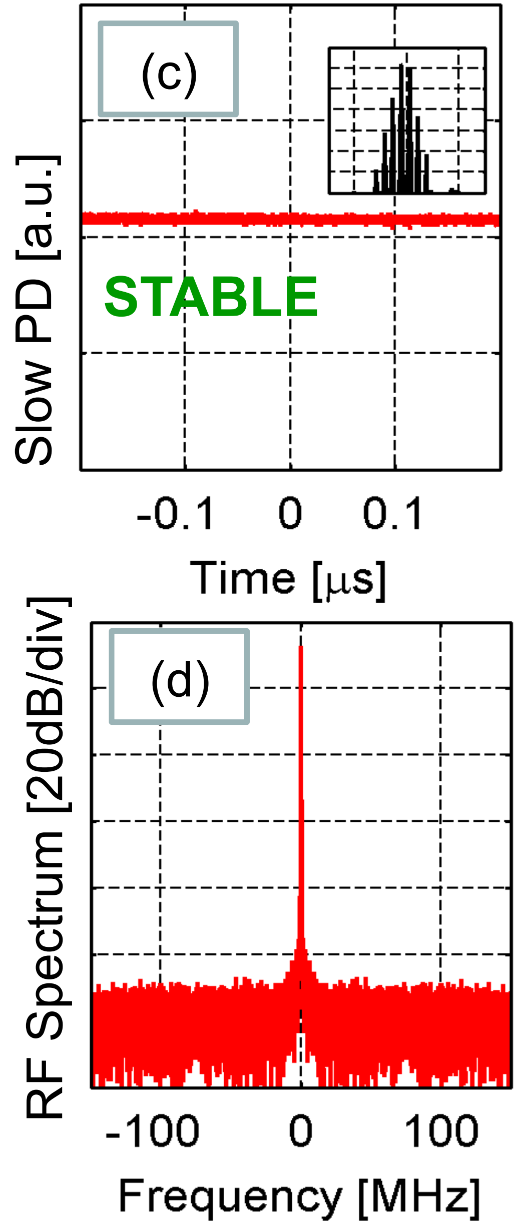
Short main cavity: single-mode per ring resonance

The main cavity has FSR=67MHz (3 meter of SMF).

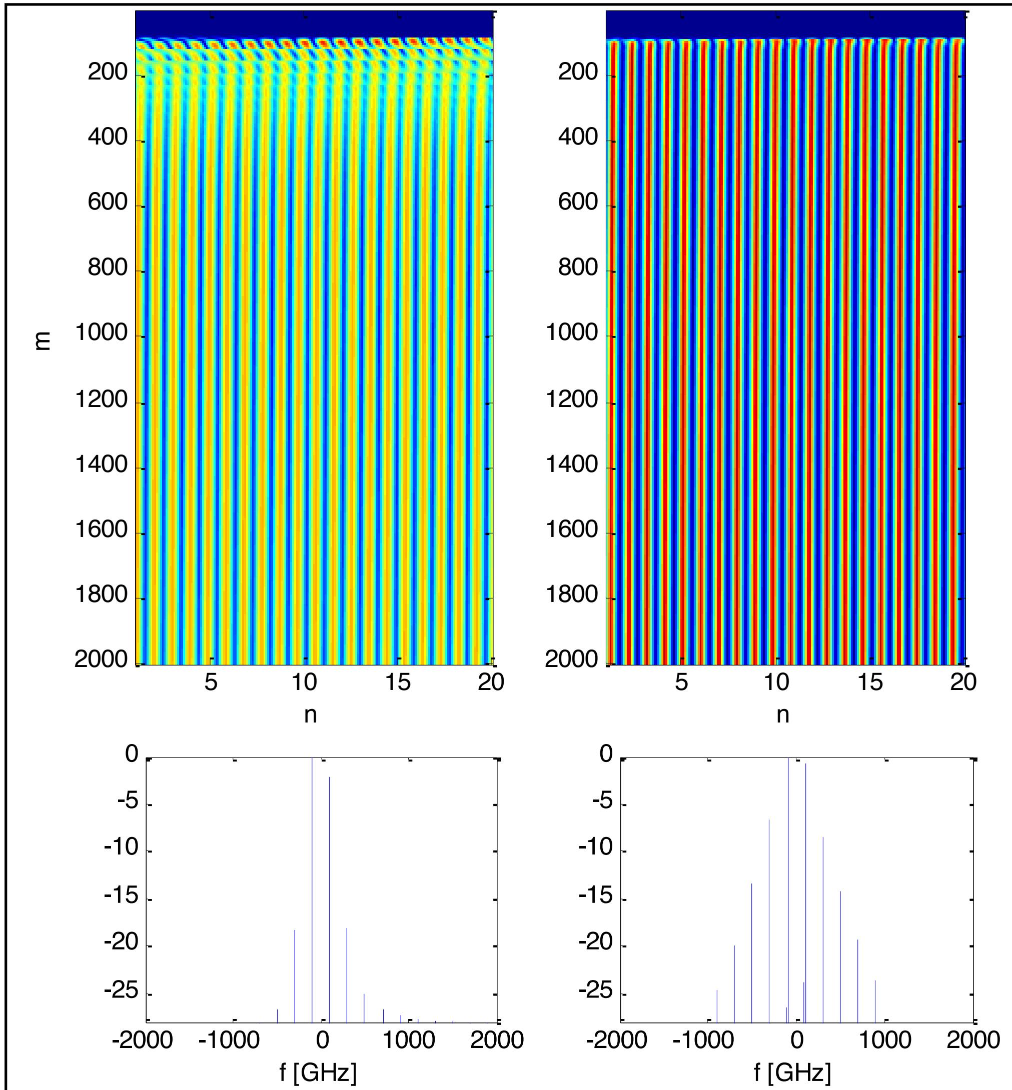
Gain 20dB saturation power 30mW



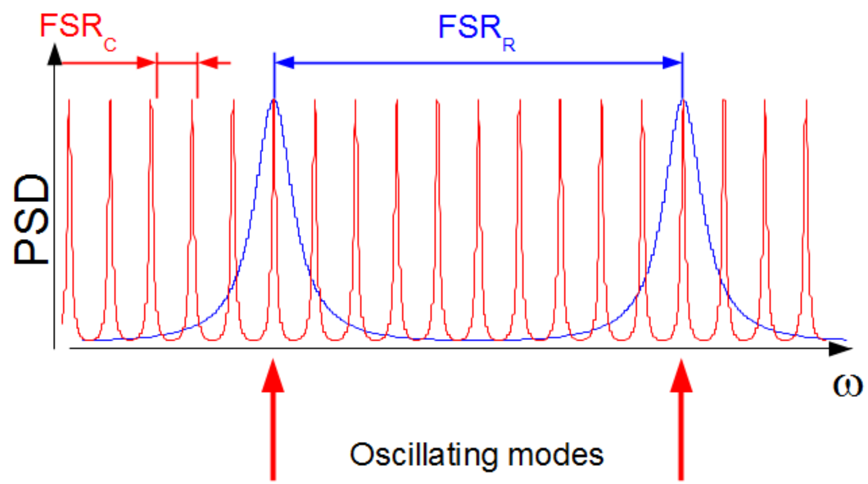
Max power in the Ring 12mW



Estimated linewith = 13KHz !!

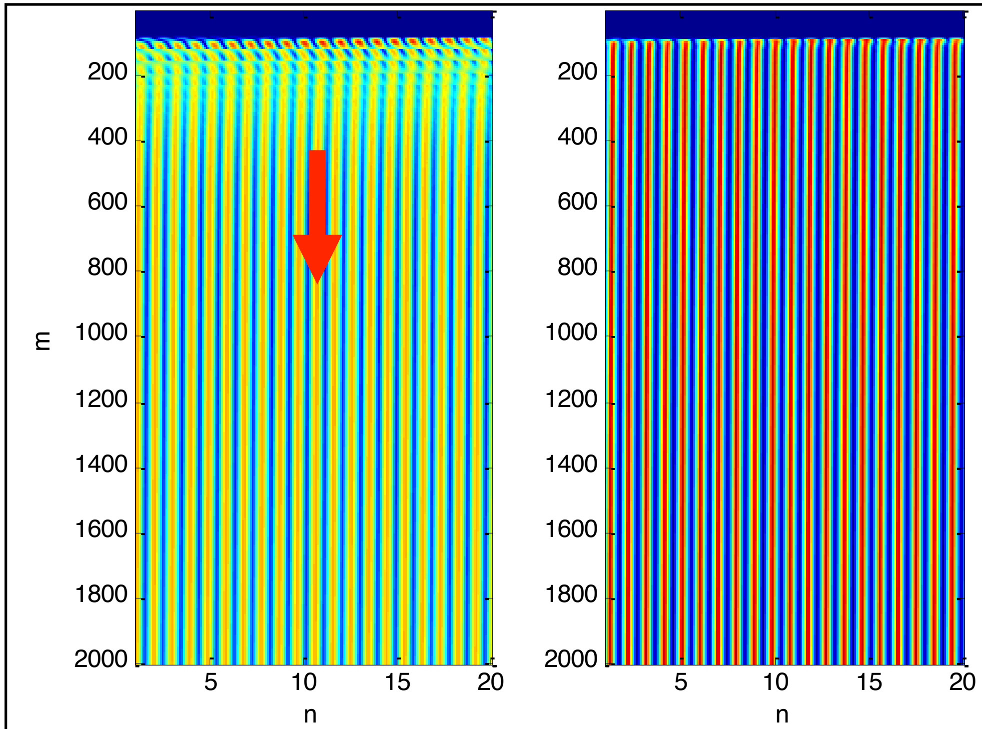


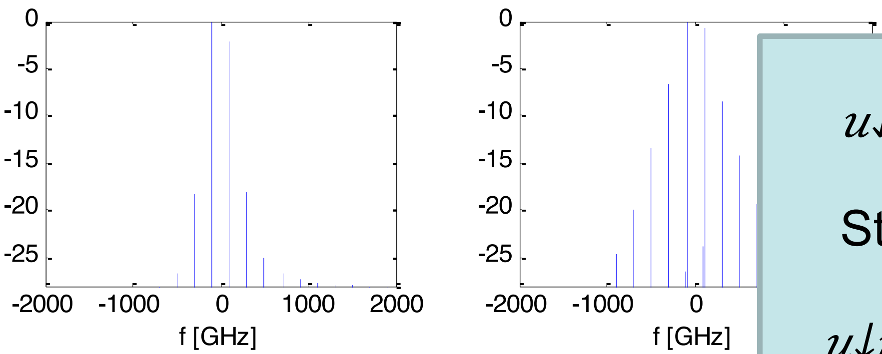
Single-mode per resonance oscillation



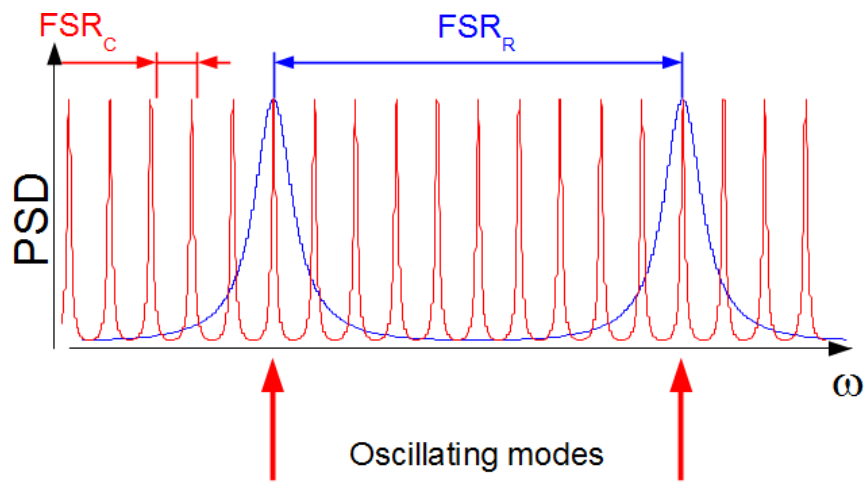
$$u_{n+1}^{m}(t)+\Gamma^{2}\, u_{n}^{m}(t)-\mathrm{K}^{2}\, u_{n}^{m-1}(t)=$$

$$\Delta\mathcal{N}[u_{n+1}^{m}(t)]+\Gamma\Delta\mathcal{N}[\Gamma u_{n}^{m}(t)]+\mathrm{K}^{2}\,\Delta\mathcal{L}[u_{n}^{m-1}(t)]$$





Single-mode per resonance oscillation



$$u_{n+1}^{m} + \Gamma^{2} u_{n}^{m} + K^{2} u_{n}^{m-1} = 0$$

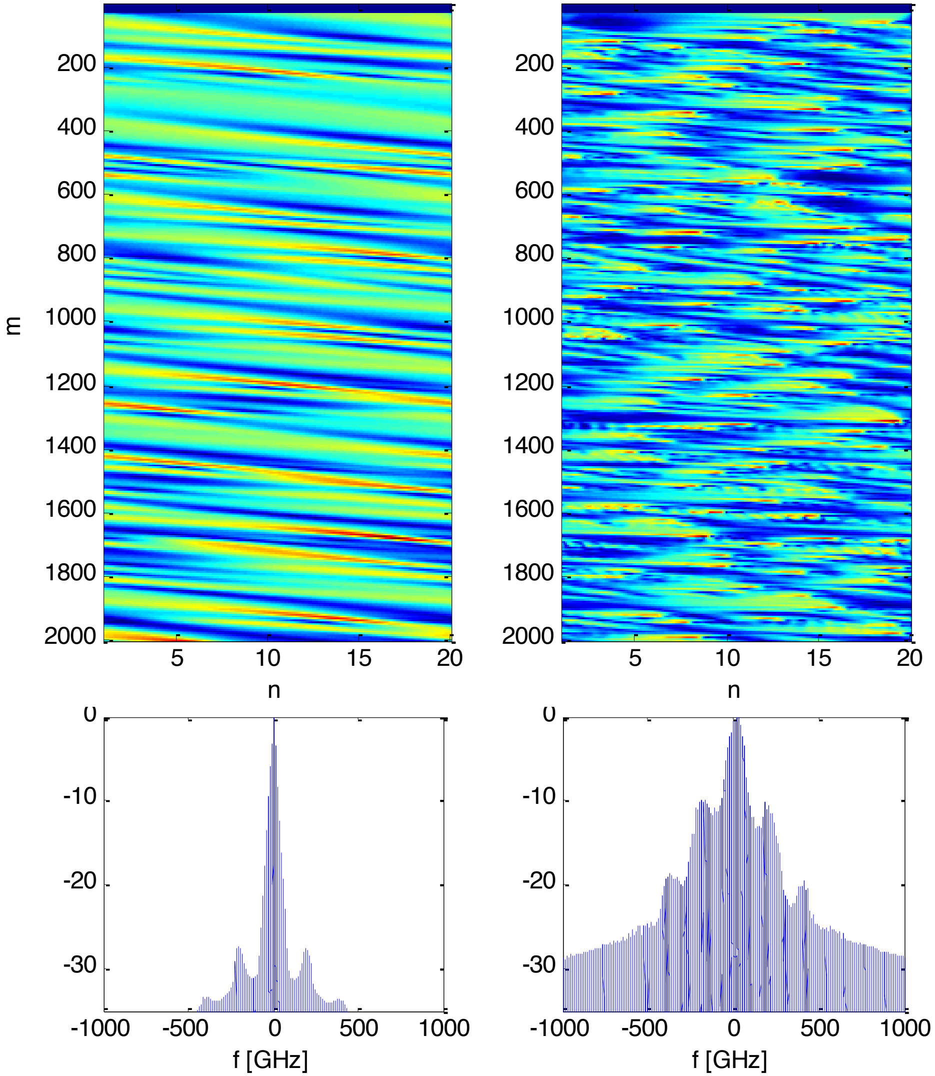
Stationary solution $u_n = -u_{n-1} = cost$

$$u_{n+1} + u_n - K^{2} \partial_m u_n = 0$$

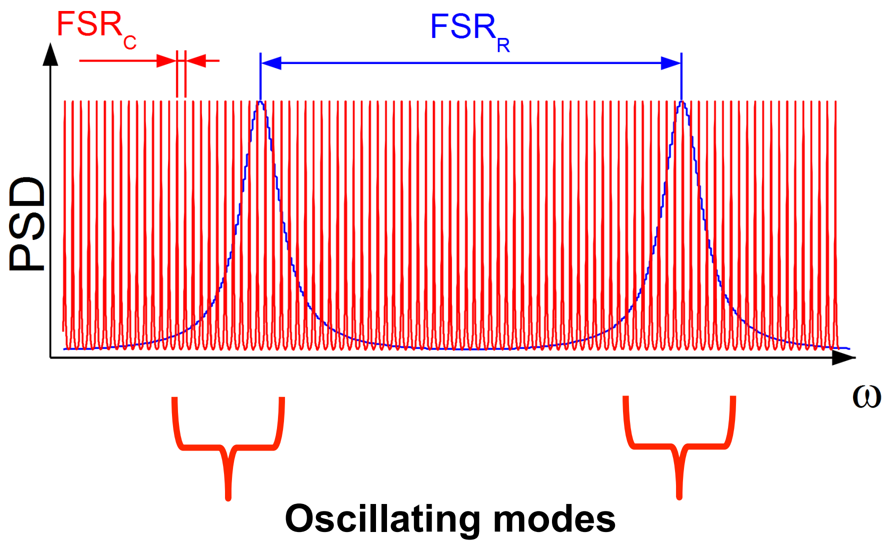
Diffusive type equation

$$u_{n+1}^{m}(t) + \Gamma^{2} u_{n}^{m}(t) + K^{2}$$

$$\Delta\mathcal{N}[u_{n+1}^{m}(t)] - \Gamma\Delta\mathcal{N}[\Gamma u_{n}^{m}(t)] - K^{2}\Delta\mathcal{L}[u_{n}^{m-1}(t)]$$

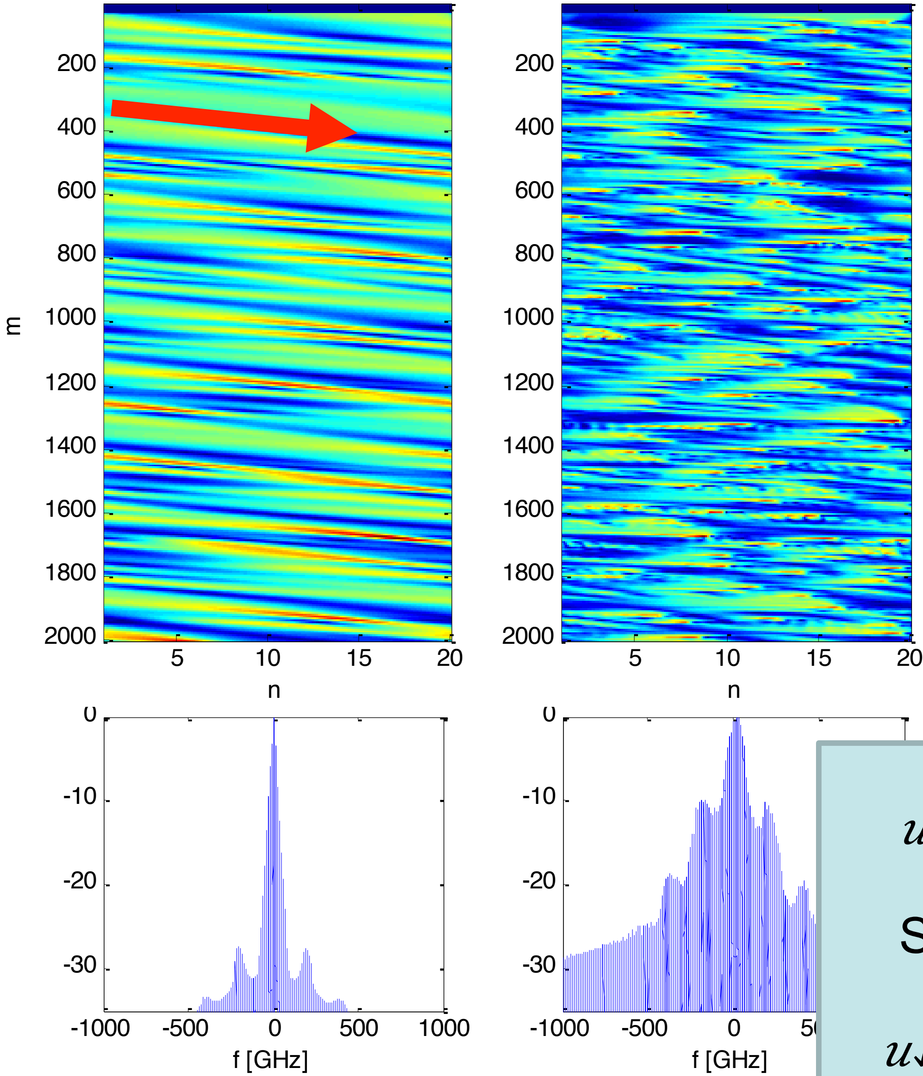


Multiple-mode per resonance oscillation

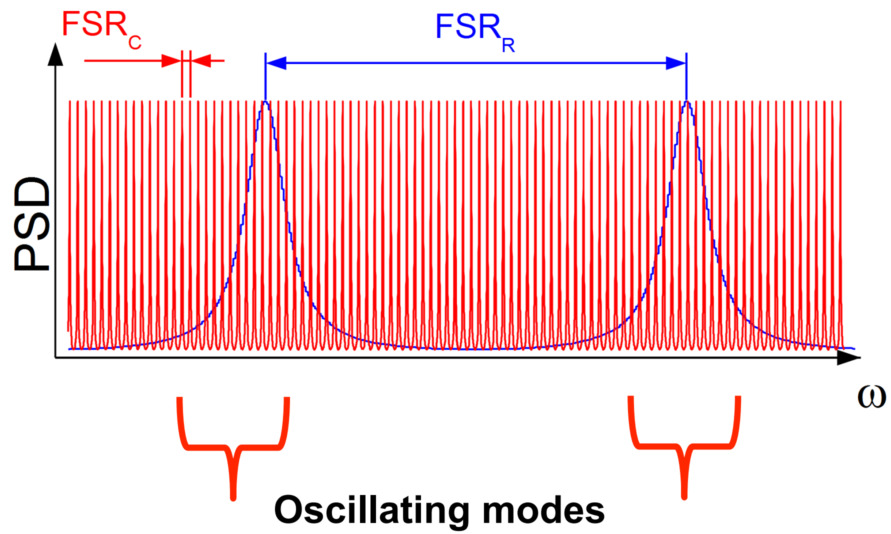


$$u_{n+1}^{m}(t) - \Gamma^{2}\, u_{n}^{m}(t) - \mathrm{K}^{2}\, u_{n}^{m-1}(t) =$$

$$\Delta\mathcal{N}[u_{n+1}^{m}(t)] + \Gamma\Delta\mathcal{N}[\Gamma u_{n}^{m}(t)] + \mathrm{K}^{2}\,\Delta\mathcal{L}[u_{n}^{m-1}(t)]$$



Multiple-mode per resonance oscillation



$$u_{n+1}^{m} - \Gamma^{2} u_{n}^{m} - K^{2} u_{n}^{m-1} = 0$$

Stationary solution $u_n = cost$

$$u_{n+1} - u_n + K^{2} \partial_m u_n = 0$$

Linear waves propagating with $1/K^{2}$ velocity

$$u_{n+1}^{m}(t) - \Gamma^{2} u_{n}^{m}(t) - K^{2}$$

$$\Delta\mathcal{N}[u_{n+1}^{m}(t)] + \Gamma\Delta\mathcal{N}[\Gamma u_{n}^{m}(t)] + K^{2}\,\Delta\mathcal{L}[u_{n}^{m-1}(t)]$$

Conclusions

University of Sussex

-DNLS can be implemented in optical lattices

-Purely nonlinear optical lattices have been presented and solitary waves have been studied and experimentally demonstrated

D (N)LS can also been implemented in synthetic temporal lattices

-Discrete modelling is an effective approach for such nested cavities design

-Viable ways to mode lock the modes of a High-Q resonator been demonstrated with a nested cavities approach

a.pasquazi@sussex.ac.uk