Discrete Photonics in Waveguide Arrays

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http://fisica.ciencias.uchile.cl/nonopt/NLOG.html
http://www.cefop.cl//

Why study physics of discrete systems?

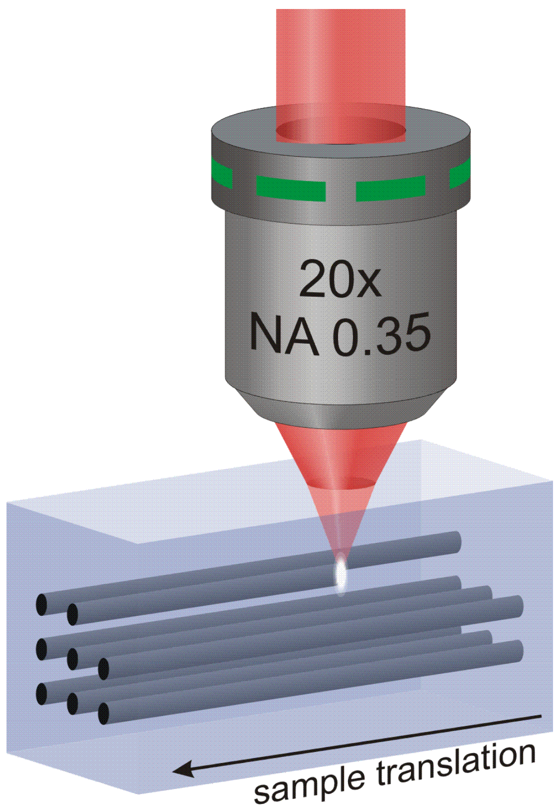
Testbed to test general phenomenology

Richer physics than continuous counterpart

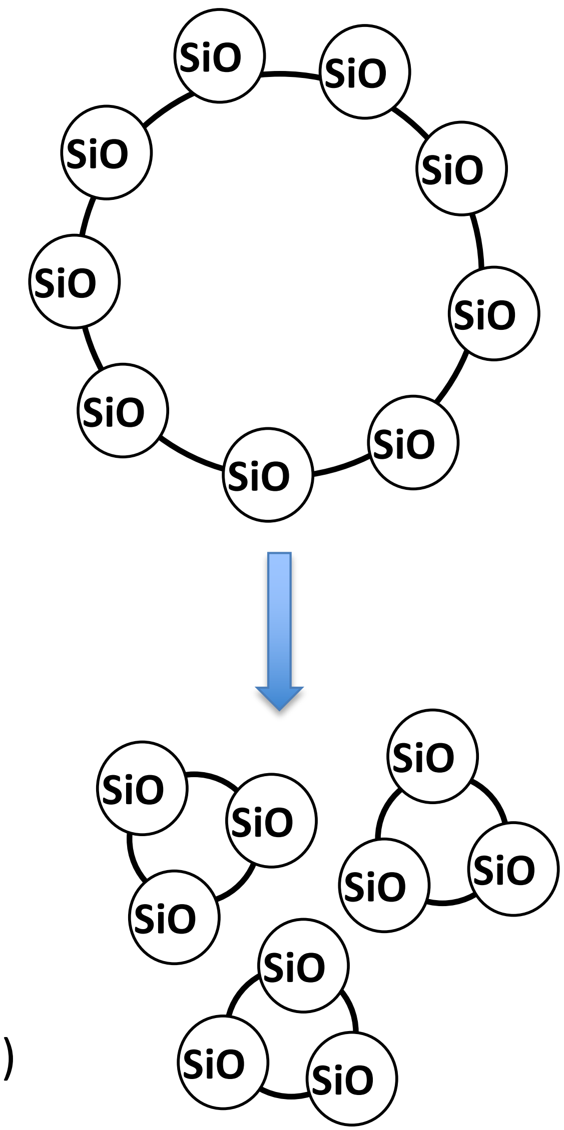
Greater potential for applications

Waveguides in fused silica

A. Szameit et al, Opt. Express 13,10552 (2005).

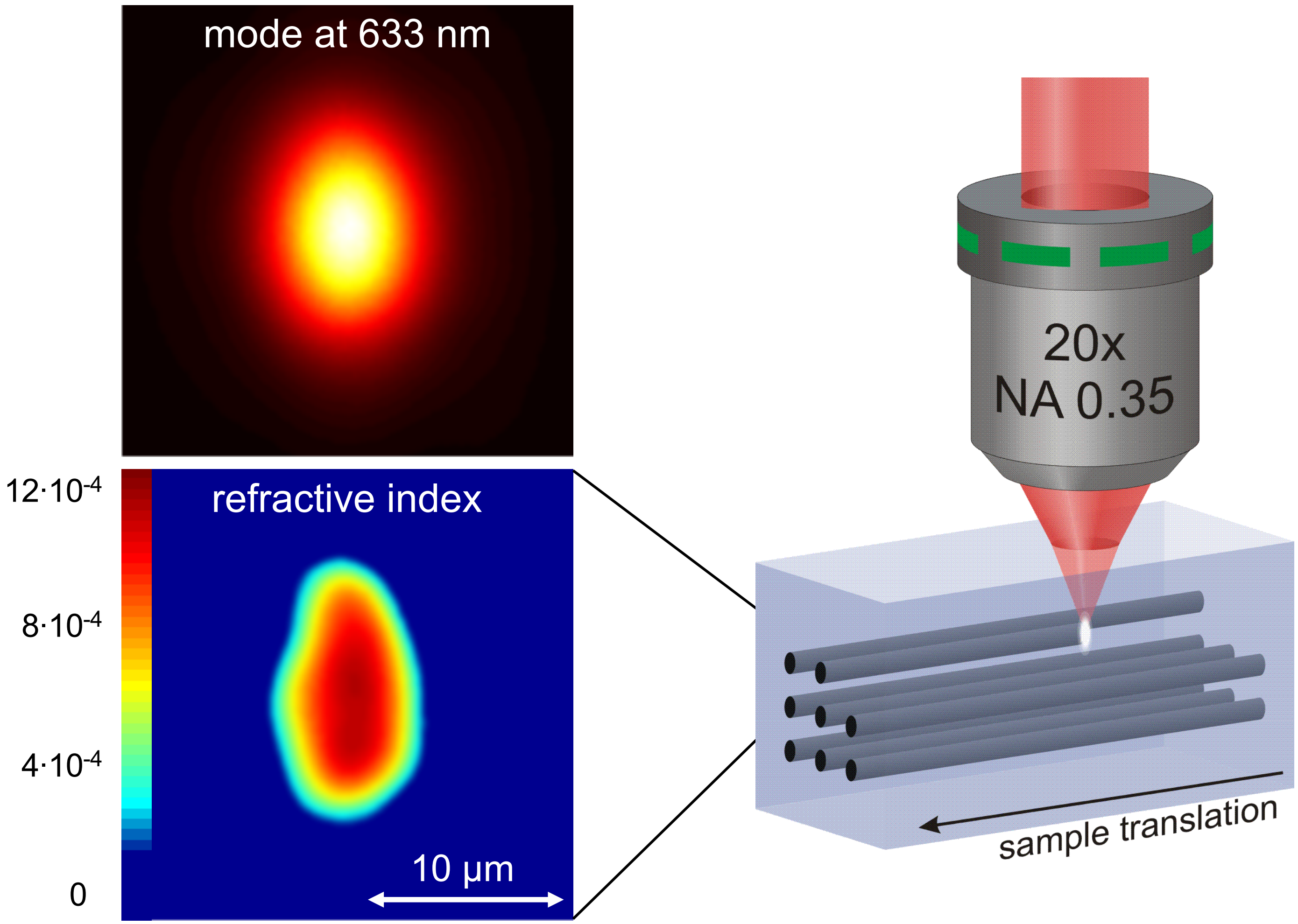


9-ring structure



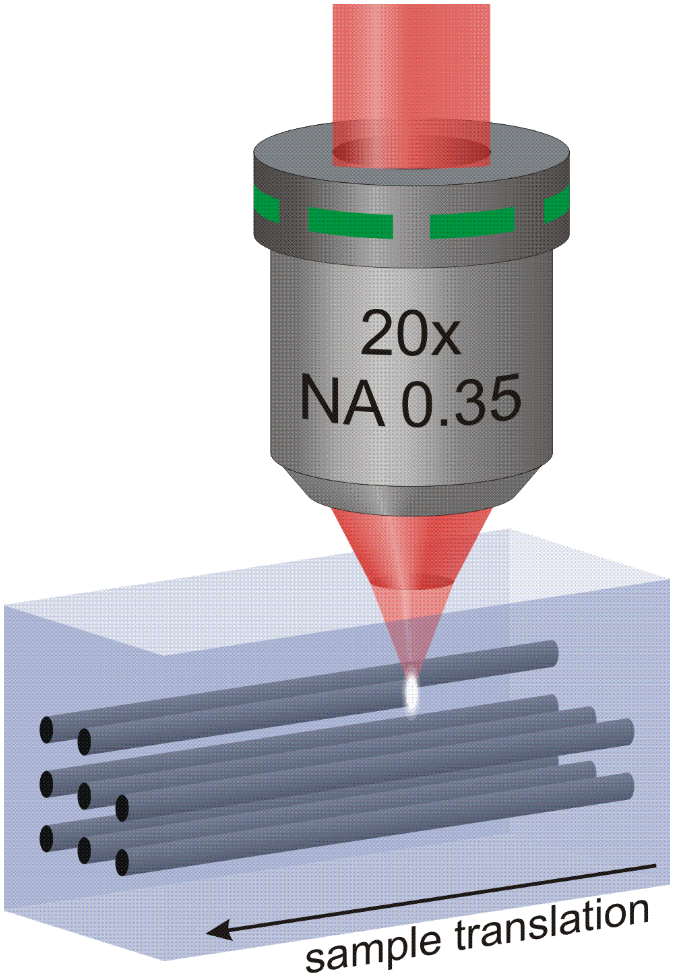
3-ring structures
(densification,
refractive index increase)

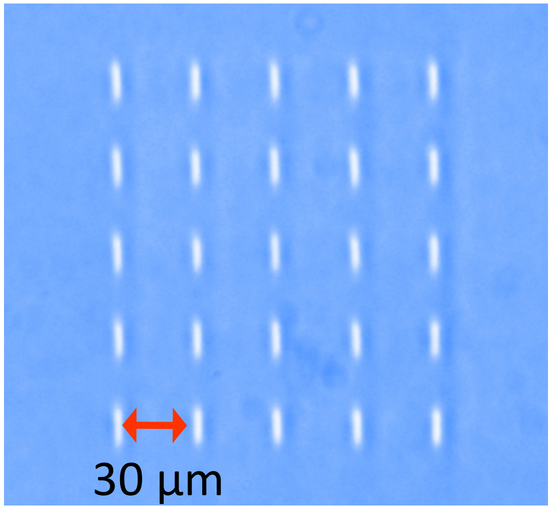
Waveguides in fused silica

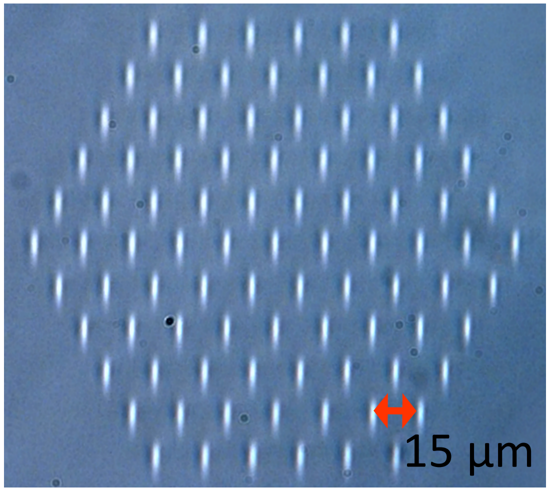


typical Δn = 10^{-3}

Waveguides in fused silica



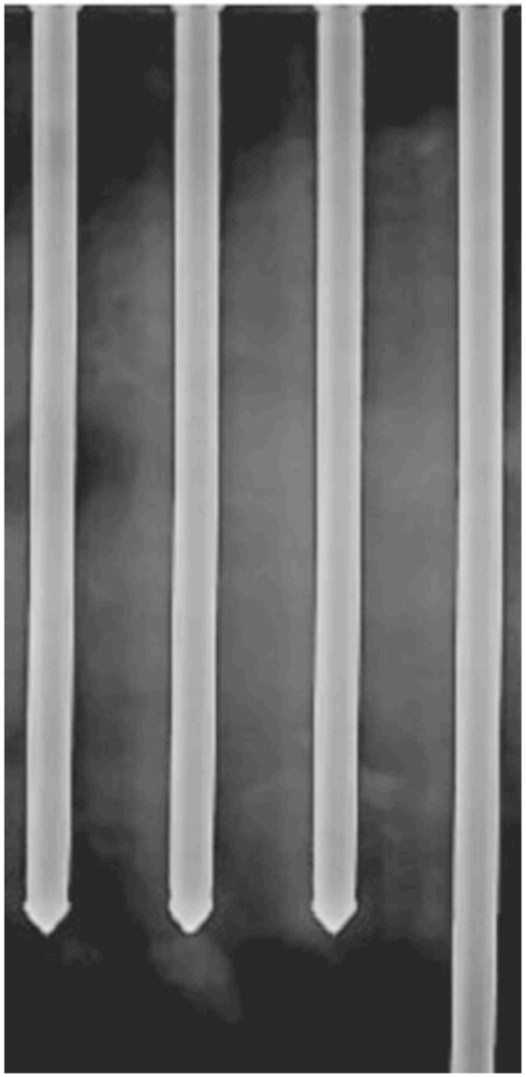


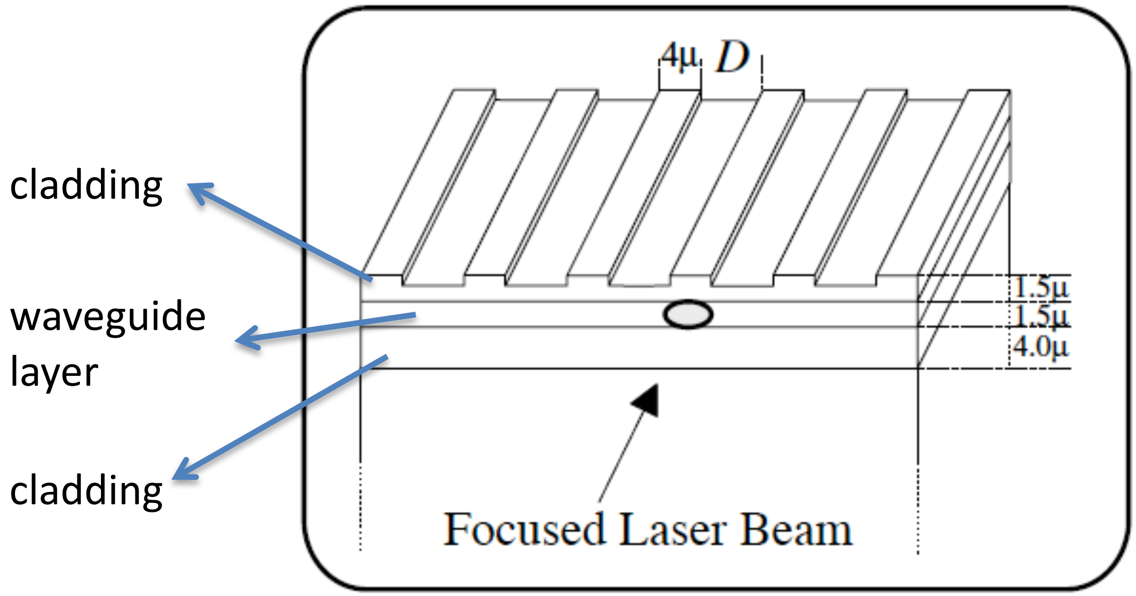


AS et al., Opt. Lett. **33**, 663 (2008).
AS et al., Appl. Phys. B **82**, 507 (2006).

Semiconductor Waveguides

P. Millar, J.S. Aitchson,J.U. Kang, G.I. Stegeman, J. Opt. Soc. Am. B 14, 3224 (1997).

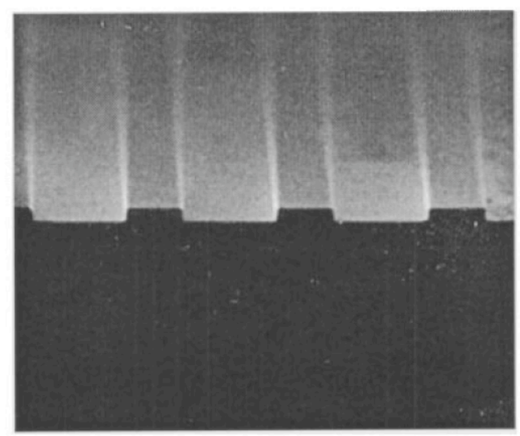




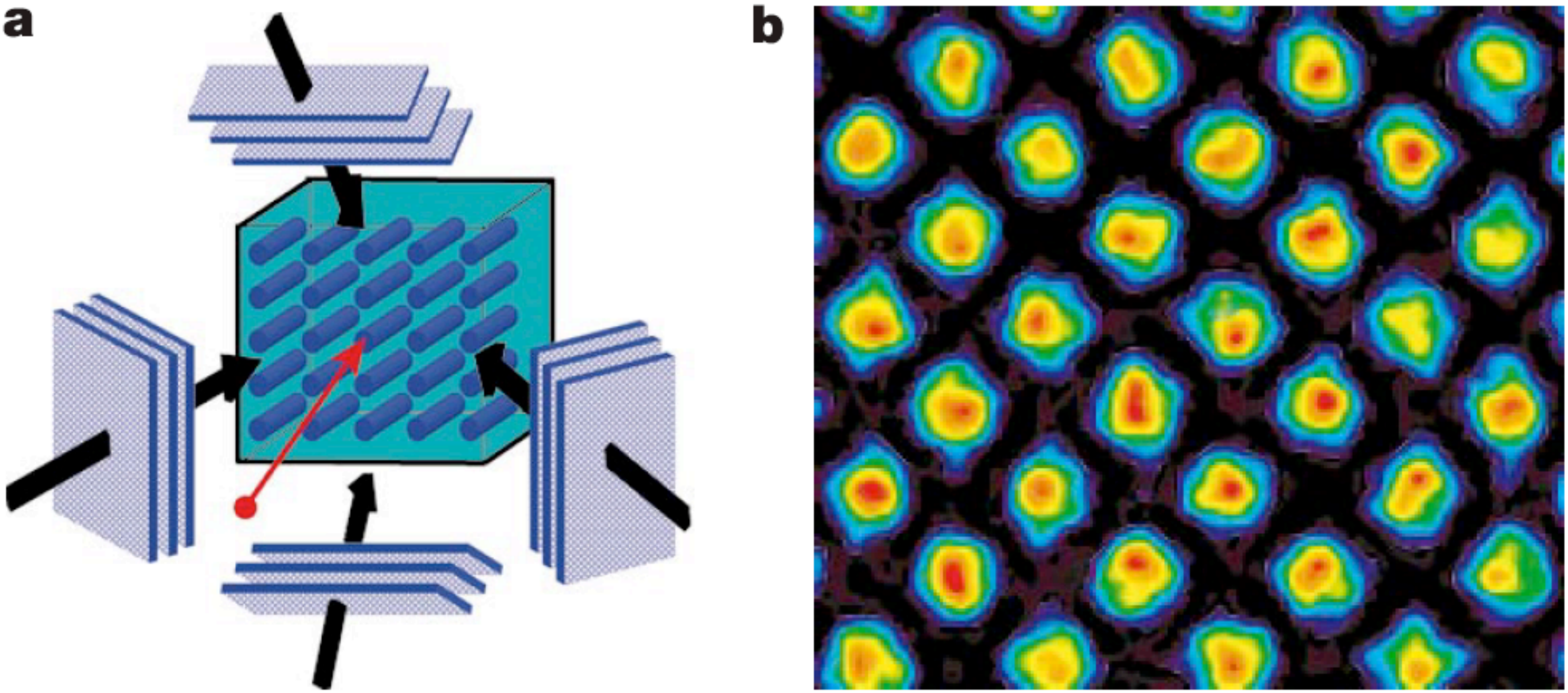
Substrate: Ga As

Cladding: $Al_{0.24}Ga_{0.76}As$

Waveguide layer:$Al_{0.18}Ga_{0.82}As$



Photorefractive Waveguides



Light→releases electrons→drift→local E fields→electro-optic effect→distribution of refractive indices

Coupled-modes theory

Maxwell:

$$\vec{\nabla} \cdot \vec{D} = 0 \qquad \vec{\nabla} \cdot \vec{B} = 0$$

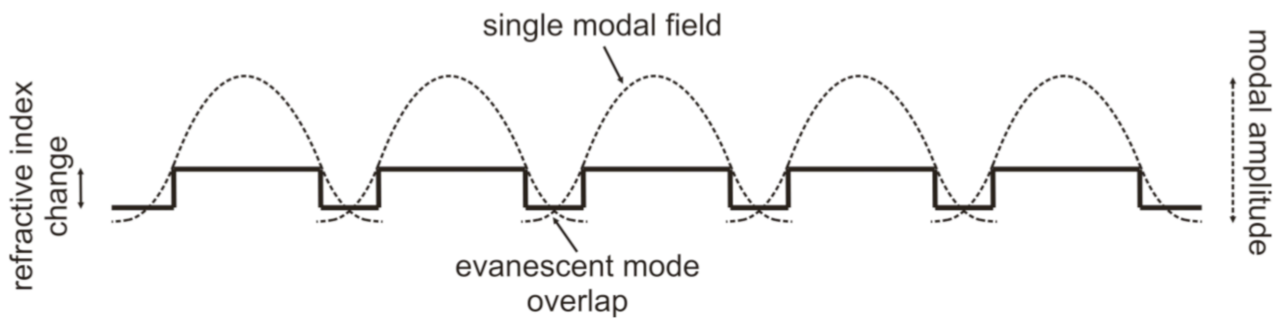
$$\vec{\nabla} \times \vec{H} = \frac{\partial}{\partial t}\vec{D} \qquad \vec{\nabla} \times \vec{E} = -\frac{\partial}{\partial t}\vec{B}$$

$$\vec{D} = \vec{E} + \vec{P} \qquad \vec{H} = \vec{B} + \vec{M}$$

$$\nabla^2 \vec{E} - \frac{1}{c^2}\frac{\partial^2 \vec{E}}{\partial t^2} = \frac{1}{c^2}\frac{\partial^2 \vec{P}}{\partial t^2}$$

$$\vec{P} = \chi^{(1)}\vec{E} + \chi^{(3)}|\vec{E}|^2\vec{E}$$

Teoría de modos acoplados



$$E(x,z) = \sum_{n=-\infty}^{\infty} C_n(z)\phi(x-x_n)$$

$$\left|\frac{d^2C_n}{dz^2}\right| \ll k_0 \left|\frac{dC_n}{dz}\right| \qquad n = n_0 + n_2|E|^2 \qquad \text{Kerr}$$

$$i\frac{dC_n}{dz} + V(C_{n+1} + C_{n-1}) + \gamma|C_n|^2 C_n = 0$$

Discrete nonlinear Schrodinger (DNLS) equation

Coupled-modes theory

$$P = \sum_n |C_n|^2$$

$$H = \sum_n \{V(C_n C^*_{n+1} + C^*_n C_{n+1}) + (\gamma/2)|C_n|^4\}$$

Conserved quantities

$$q_n = C_n; \qquad p_n = i\ C^*_n$$

$$(d/dt)q_n = \partial H/\partial p_n \qquad (d/dt)p_n = -\partial H/\partial q_n$$

Hamiltonian system

$$C_n = u_n \exp(i\beta z)$$

Stationary mode

$$-\beta u_n + (u_{n+1} + u_{n-1}) + \chi|u_n|^2 u_n = 0$$

Nonlinear eigenvalue equation

Coupled-modes theory

Finding the localized nonlinear mode

$$-EC_n + V(C_{n+1} + C_{n-1}) + \chi|C_n|^2 C_n = 0$$

$$\lambda \equiv E/V, \qquad \phi_n \equiv \sqrt{\chi/V}\,C_n$$

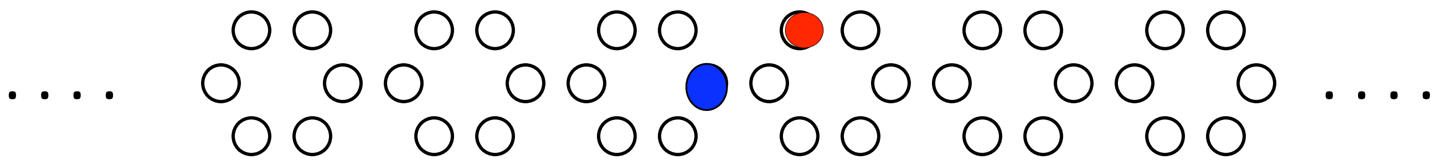
$$-\lambda\phi_n + (\phi_{n+1} + \phi_{n-1}) + |\phi_n|^2\phi_n = 0$$

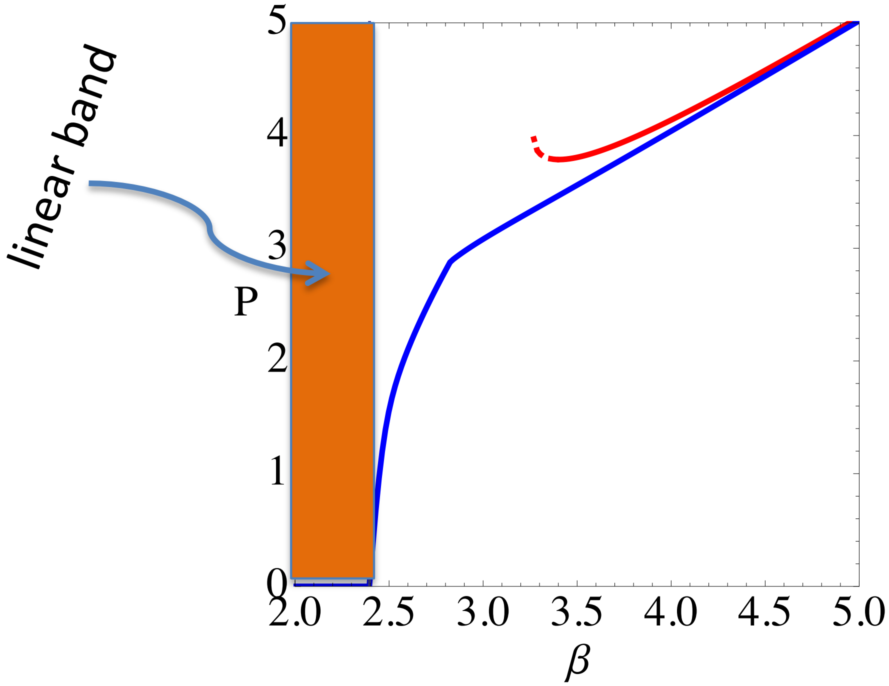
$$\vec{F}(\vec{\phi}) = 0 \quad \text{use Newton-Raphson}$$

Need good seed (anticontinuous limit)
Find many solution families (characterized by power
vs prop.const. curve

Coupled-modes theory

Example: Graphene ribbon



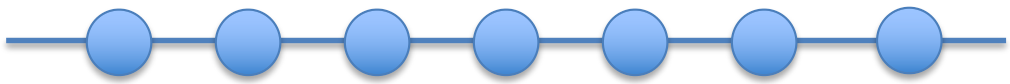


$$P = \sum_n |\phi_n|^2$$

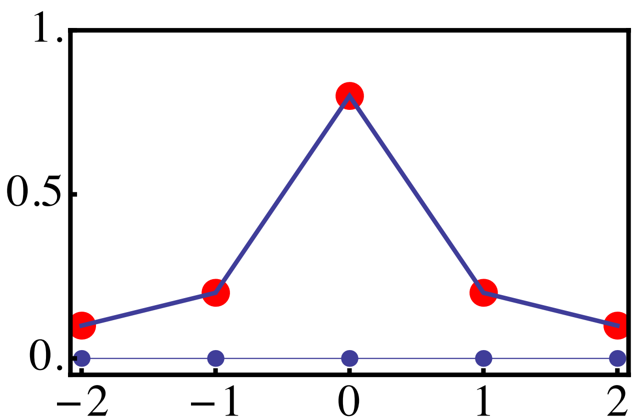
Conserved quantity

Coupled-modes theory

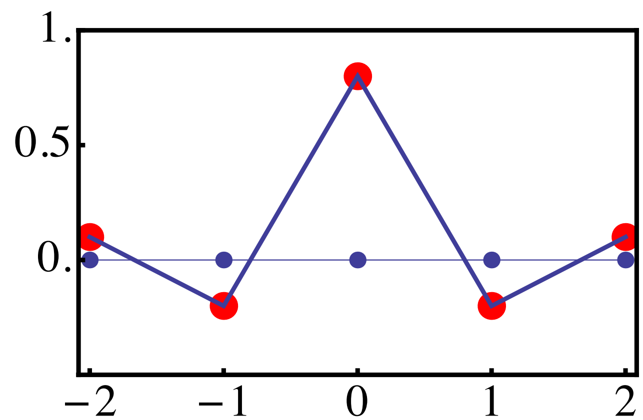
Pure 1D CASE



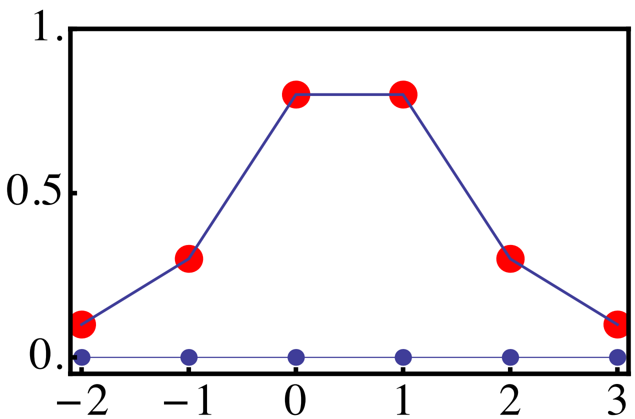
odd unstaggered



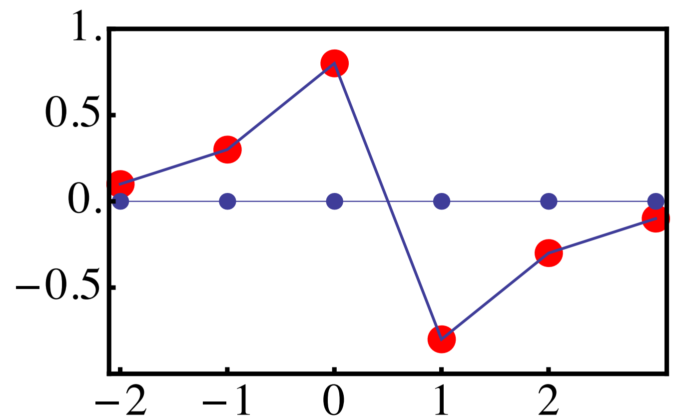
odd staggered



even



twisted



Linear stability

$$C_n(z) = \phi_n e^{-i\lambda z} \qquad \text{sol. of DNLS}$$

$$C_n(z) \to (\phi_n + \delta\phi_n) e^{-i\lambda z}, \qquad |\delta\phi_n/\phi_n| \ll 1$$

$$\Longrightarrow \quad \text{Equation for } \; \delta\phi_n = \delta u_n + i\delta v_n$$

$$\text{define } \delta\vec{u} = (\delta u_1, \delta u_2, ..., \delta u_N), \qquad \delta\vec{v} = (\delta v_1., \delta v_2, ..., \delta v_N)$$

$$\mathcal{A}_{nm} = \delta_{n,m+1} + \delta_{n,m-1} + (\lambda + \phi_n^2)\delta_{n,m}$$

$$\mathcal{B}_{nm} = \delta_{n,m+1} + \delta_{n,m-1} + (\lambda + 3\phi_n^2)\delta_{n,m}$$

$$\boxed{\delta\ddot{\vec{U}} + \mathcal{B}\mathcal{A}\;\delta\vec{U} = 0 \;\; \text{and} \;\; \delta\ddot{\vec{V}} + \mathcal{A}\mathcal{B}\;\delta\vec{V} = 0}$$

Coupled-modes theory

$$\{\mathrm{m}\}\text{=eigenvalues of } \mathcal{AB} = \text{eigenvalues of } \mathcal{BA}$$

instability gain

$$G^* = \mathrm{Max}\left\{\sqrt{(1/2)(-\mathrm{Re}[\mathrm{m}] + \sqrt{\mathrm{Re}[\mathrm{m}]^2 + \mathrm{Im}[\mathrm{m}]^2})}\right\}$$

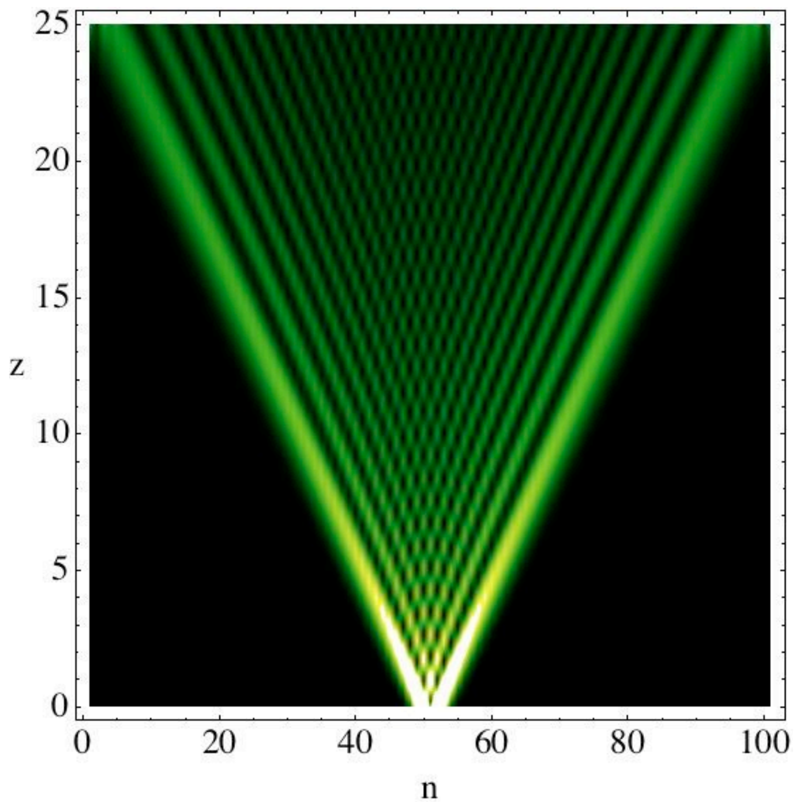
$$G^* = 0 \quad \text{stable}$$

$$G^* > 0 \quad \text{unstable}$$

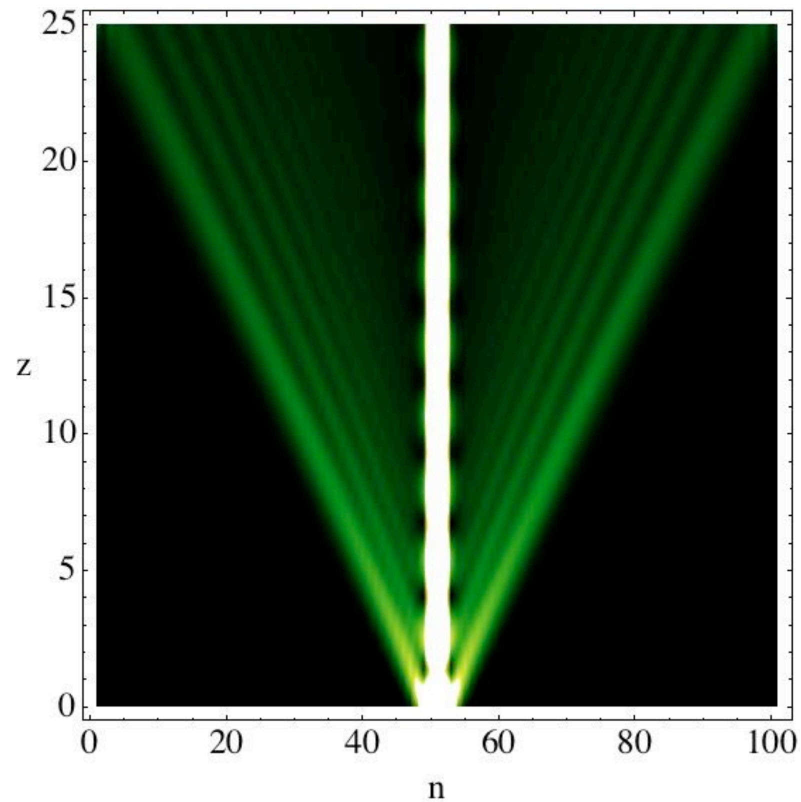
Coupled-modes theory

Numerical propagation

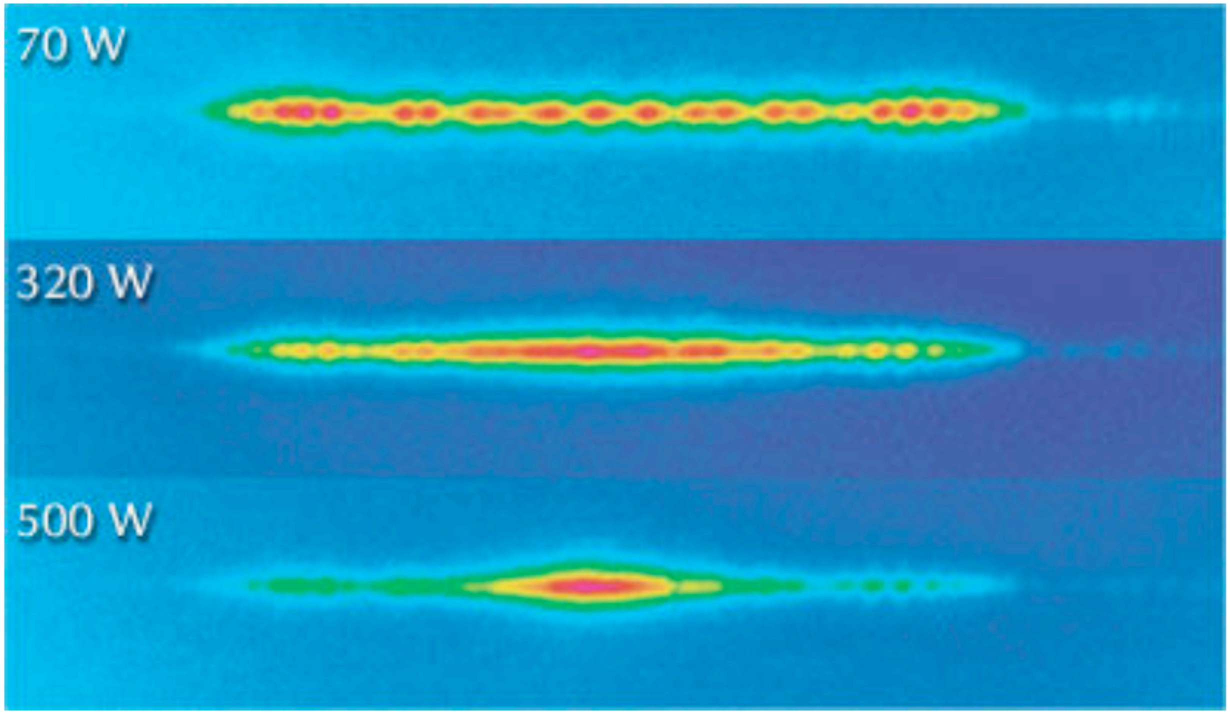
Discrete diffraction



Discrete soliton formation



First experimental observation of discrete soliton



Difraccion discreta

Soliton discreto

H. Eisenberg at al, PRL 81, 3383 (1998).