Nonlinear dynamics of exciton-polaritons loaded into periodic lattices

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❖ Dr. E.A. Ostrovskaya

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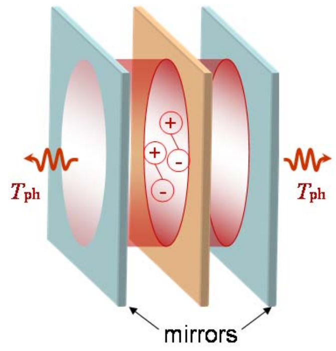
❖ Dr. K. Winkler and Dr. C. Schneider

Technische Physik, Wilhelm-Conrad-Röntgen-Research Center for Complex Material Systems, Universität Würzburg, Germany

Outline

✓ Introduction

- *strong light-matter coupling*
- *exciton-polaritons in photonic lattices*

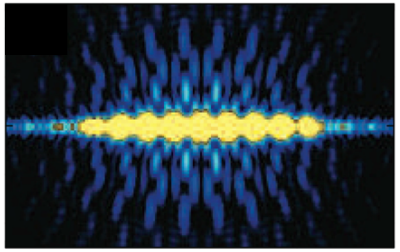


✓ Exciton-polaritons in 1D weak-contrast lattices

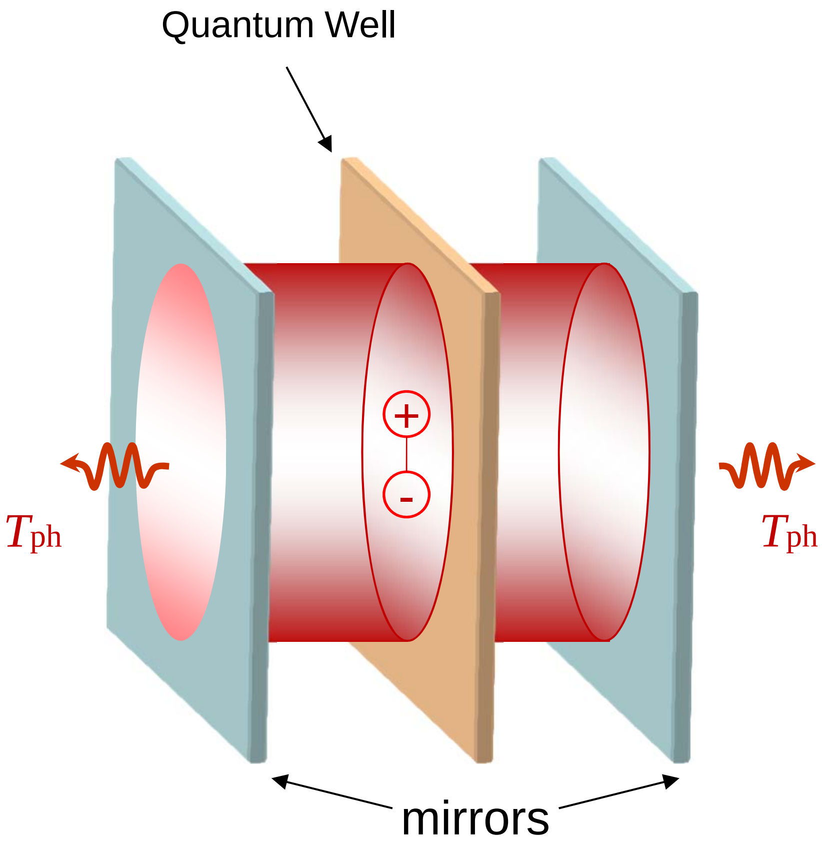
- *π -state oscillations*
- *nonlinear Bloch-Modes*

✓ Controlled loading into chain of coupled mesas

- *chain of coupled mesas*
- *emission from higher Bloch modes*
- *Talbot patterns*



Strong coupling



Strong coupling – exciton-polaritons

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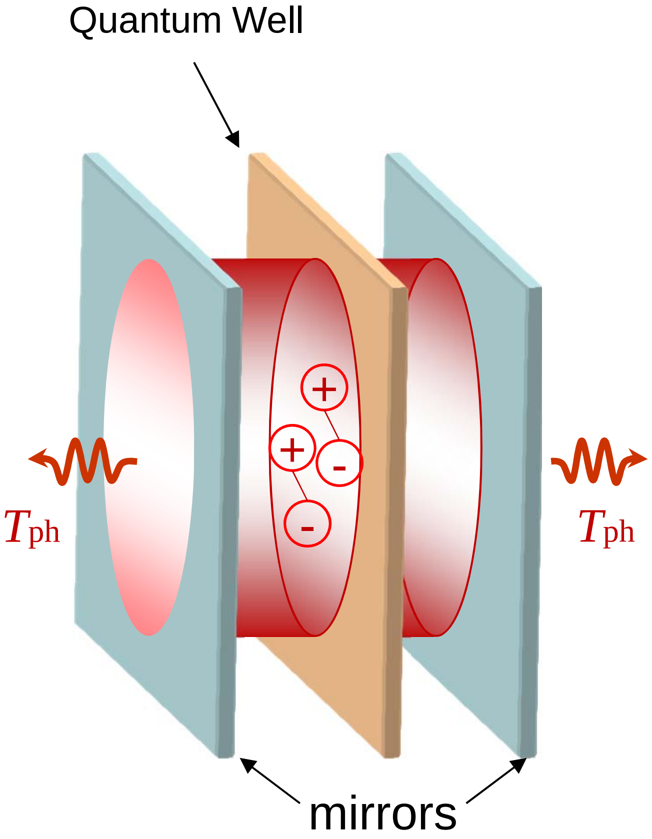
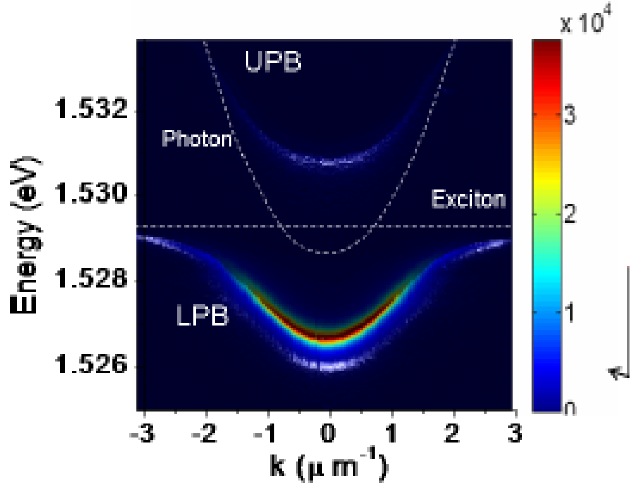


Experiment (luminescence)



D. Sanvitto *et al.*,
Nanotechnology **21**, 134025 (2010)

cavity photon + exciton ⇒
exciton-polariton

J.J.Hopfield, Phys. Rev. ***112****, 1555 (1958),*
Weisbuch et al., PRL ***69****, 3314, (1992)*

Strong coupling – condensation

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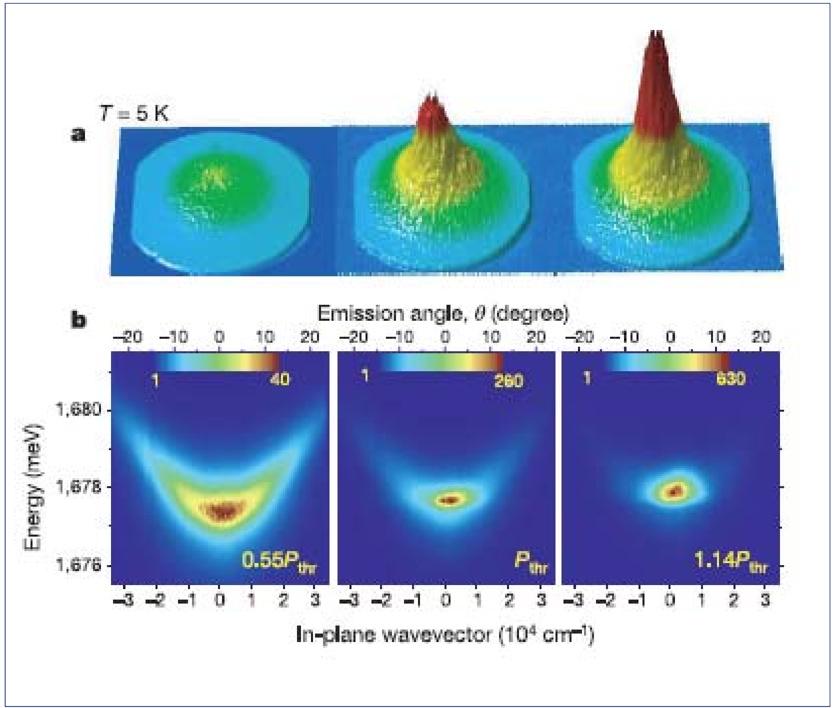
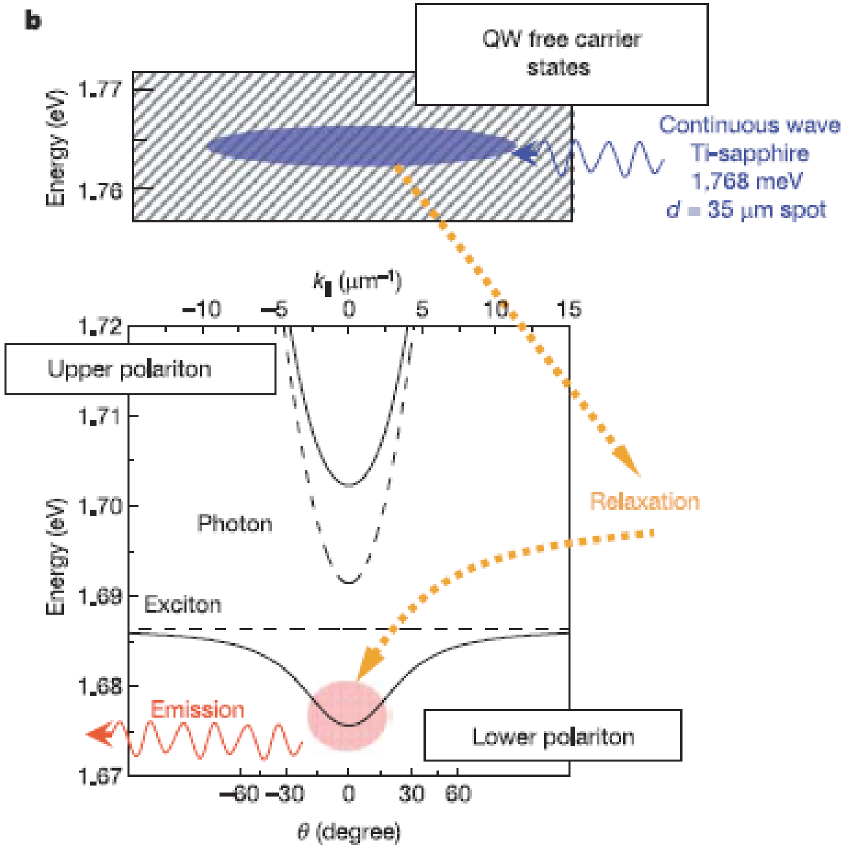
Nonequilibrium BEC of polaritons





J. Kasprzak et. al., Nature ***443****, 05131 (2006);*
H.Deng, H.Haug and Y.Yamamoto, Rev. of Mod. Phys. ***82****, 1489, (2010)*

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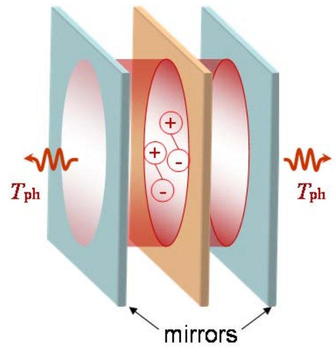

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- π -state oscillations

- nonlinear Bloch-Modes

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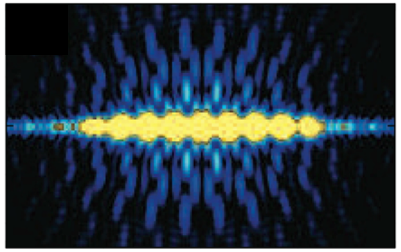
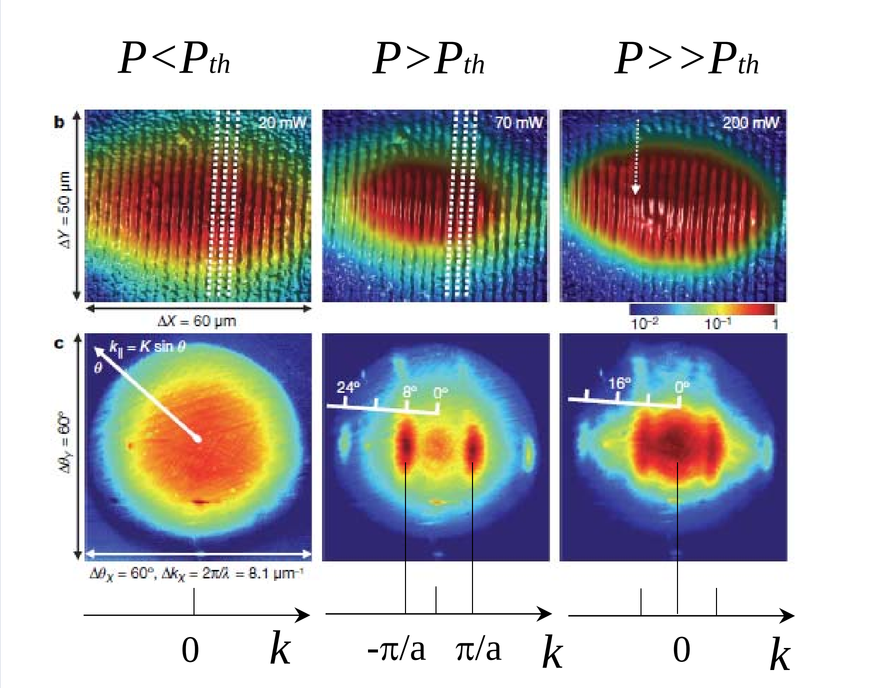
- chain of coupled mesas

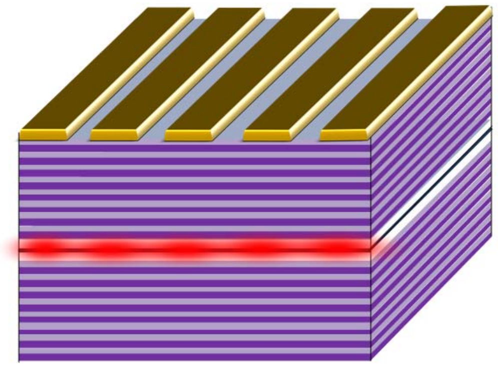
- emission from higher Bloch modes

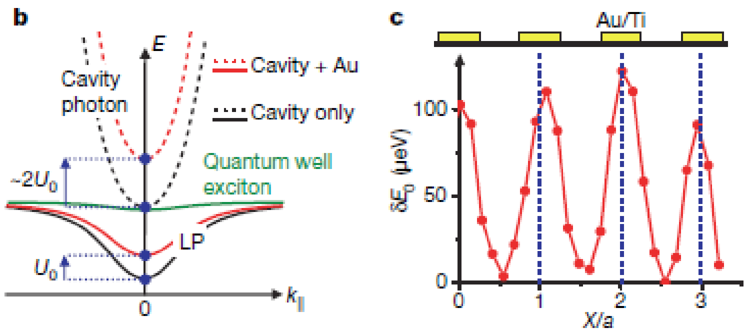
- Talbot patterns



π -states vs. ground states in lattices



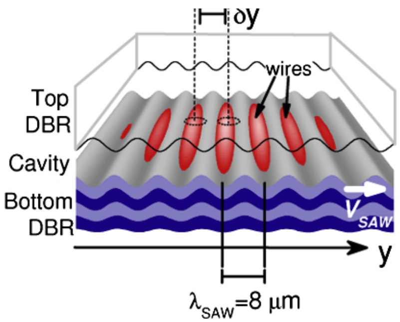


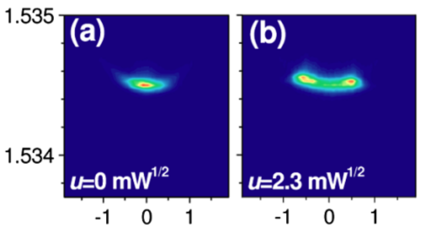


*C.W. Lai et. al., Nat. Lett. **450**, 529 (2007)*

π -states vs. ground states in lattices

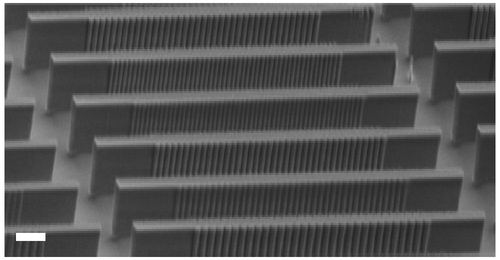
Acoustic Lattices

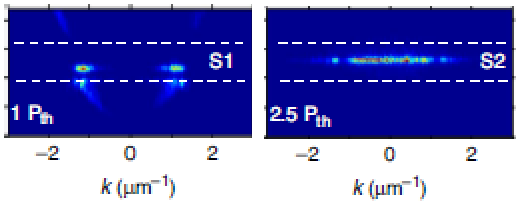




E.A. Cerda-Mendez *et al.*,
Phys. Rev. Lett. **105**, 116402 (2010)

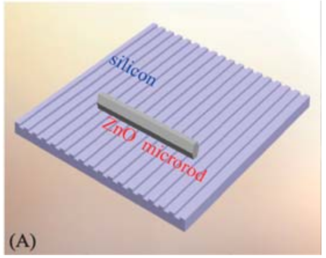
Modulated polaritonic wires

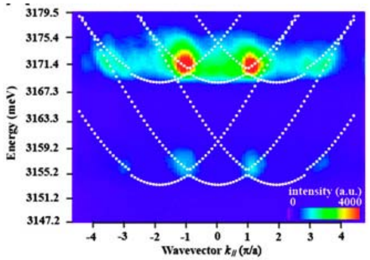




D. Tanese *et al.*, Nature Comm. **4**,
1749 (2013)

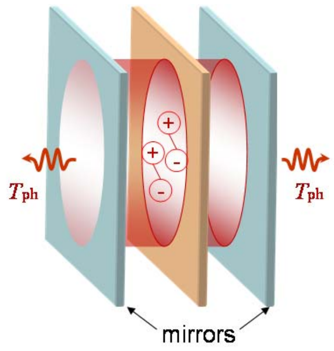
ZnO-wire on silicon grating





L. Zhang *et al.*, Proc. of Nat. Academy
of Sci. of USA **112**, 1516 (2015)

Outline



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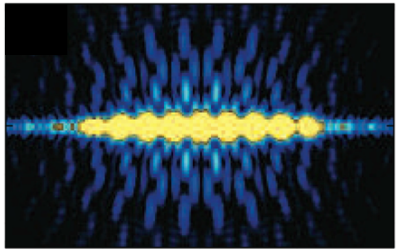
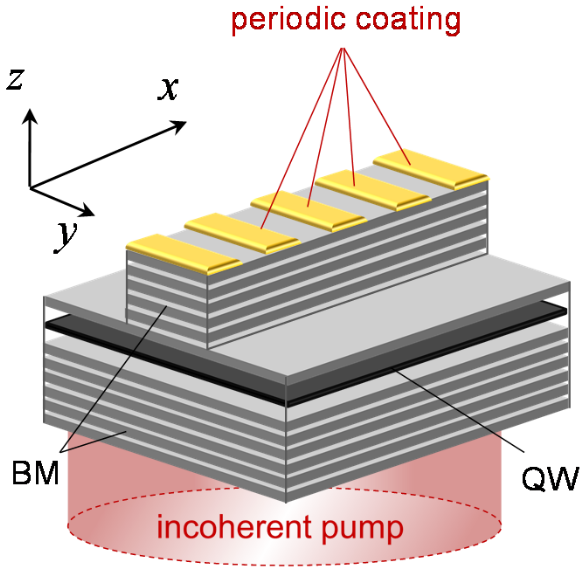


1D weak-contrast lattices



Gross-Pitaevskii dissipative model

$$i\hbar\frac{\partial\psi}{\partial t}=\left[-\frac{\hbar^2}{2m}\frac{\partial}{\partial x^2}+V(x)+g_c|\psi|^2+i\Gamma(n)\right]\psi$$

$$\Gamma(n)=\tfrac{\hbar}{2}\left(Rn-\gamma_c\right)-ig_r n$$

Incoherent reservoir (gain and losses)

$$\frac{\partial n}{\partial t}=-\left(\gamma_r+R|\psi|^2\right)n+P_0$$

Photonic weak-contrast lattice

$$V(x)=V_0\cos(2\pi x/l) \qquad l=8\mu m$$

$$\gamma_c=0.66\gamma_r=0.33ps^{-1}$$

$$g_c=0.5g_r=6\times10^{-3}meV\mu m^2$$

$$R=0.01ps^{-1}\mu m^2$$

M. Wouters et. al., Phys. Rev. Lett. ***99****, 140402 (2007)*

C.W. Lai et. al., Nat. Lett. ***450****, 529 (2007)*

1D weak-contrast lattices

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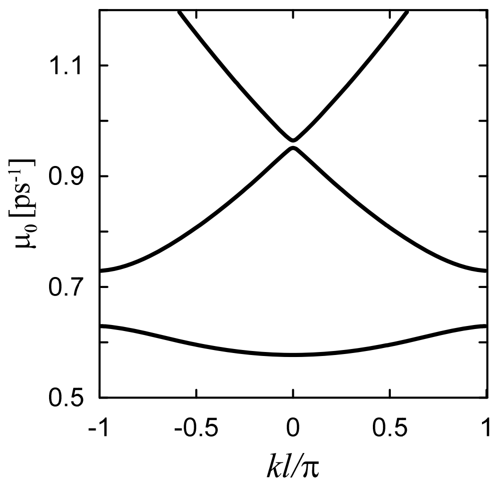


Dispersion relation
(linear limit)

In form of Bloch waves
(linear limit)

$$\psi(x,t) = \psi_{BM}(x;k) \cdot e^{-i\mu_0(k)t + ikx}$$

Gross-Pitaevskii dissipative model

$$i\hbar \frac{\partial \psi}{\partial t} = \left[-\frac{\hbar^2}{2m} \frac{\partial}{\partial x^2} + V(x) + g_c |\psi|^2 + i\Gamma(n) \right] \psi$$

$$\Gamma(n) = \tfrac{\hbar}{2}\left(Rn - \gamma_c\right) - i g_r n$$

Incoherent reservoir (gain and losses)

$$\frac{\partial n}{\partial t} = -\left(\gamma_r + R|\psi|^2\right) n + P_0$$

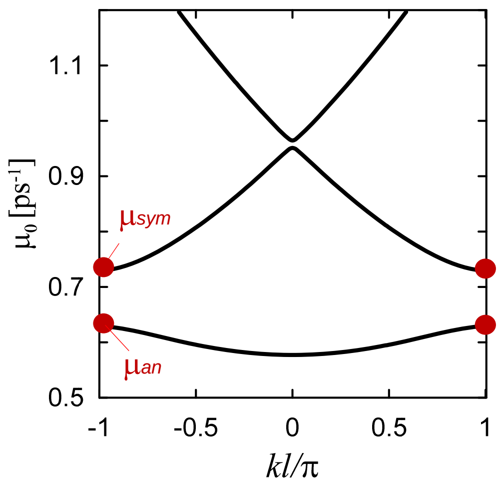
Photonic weak-contrast lattice

$$V(x) = V_0 \cos(2\pi x / l) \qquad l = 8\mu m$$

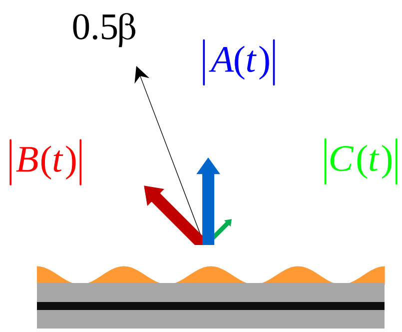
M. Wouters et. al., Phys. Rev. Lett. ***99****, 140402 (2007)*

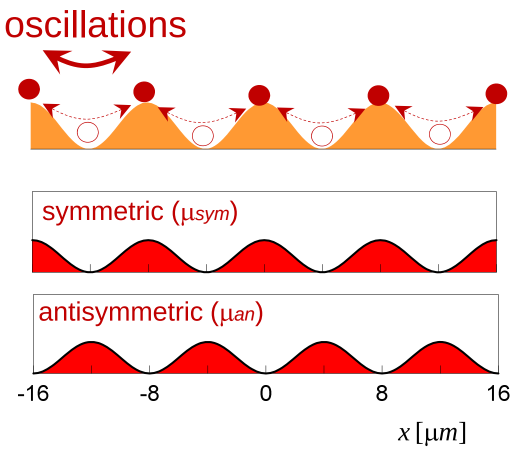
C.W. Lai et. al., Nat. Lett. ***450****, 529 (2007)*

1D weak-contrast lattices – oscillations



Dispersion relation
(linear limit)



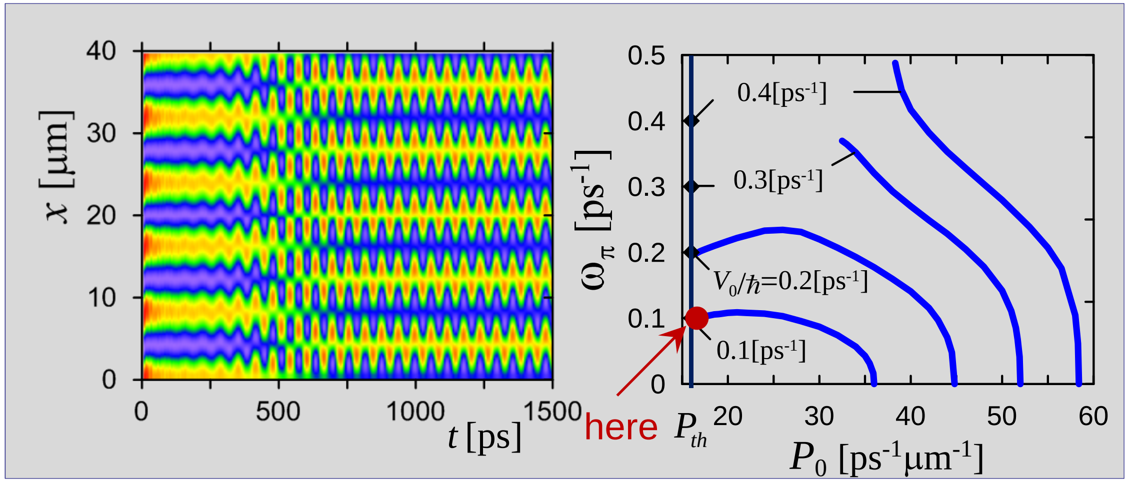


Saturation of the gain

(spatial hole burning)

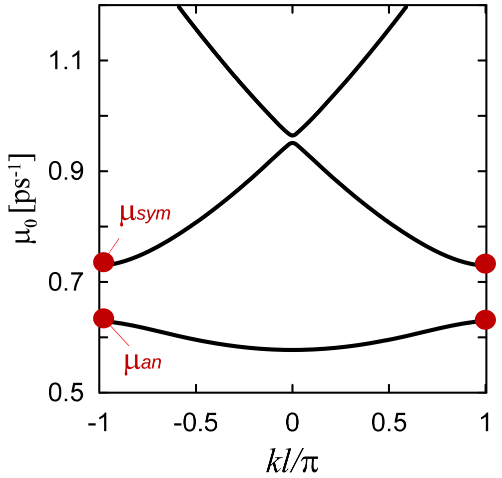
$V_0/\hbar = 0.1ps^{-1}$

$P_0 = 18\,ps^{-1}\mu m^{-2}$

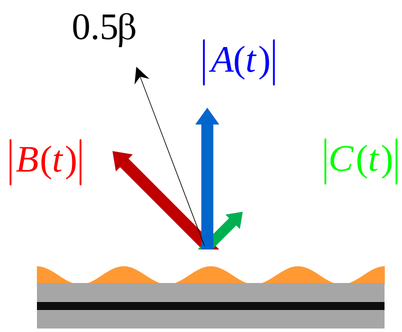


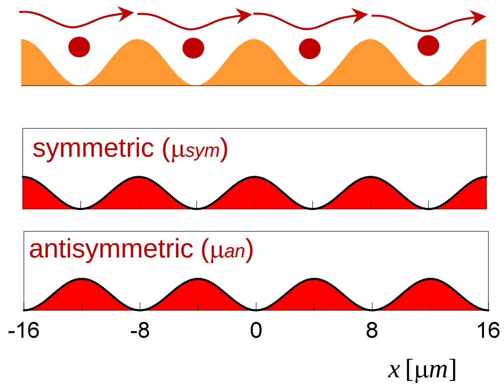
X. Ma et. al., Phys. Rev. B ***91****, 214301 (2015)*

1D weak-contrast lattices – tunneling



Dispersion relation
(linear limit)



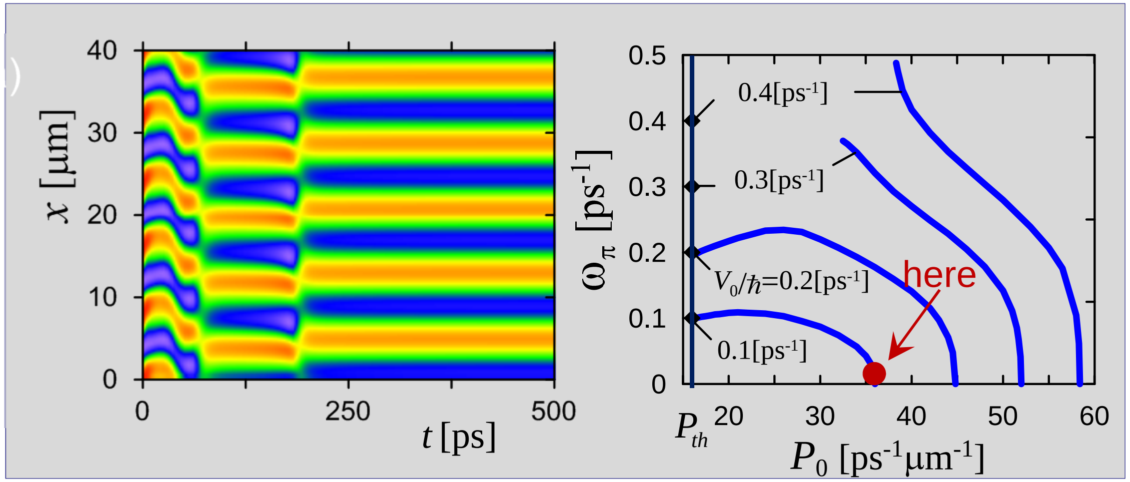


Nonlinear effects:

screening of potentials

$V_0/\hbar = 0.1ps^{-1}$

$P_0 = 36\,ps^{-1}\mu m^{-2}$



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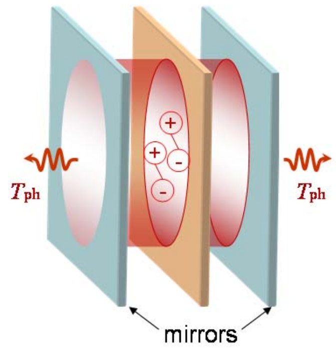
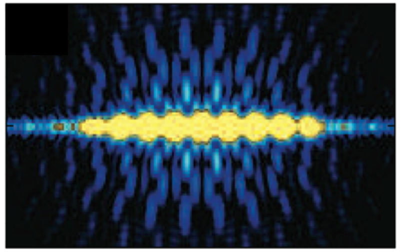
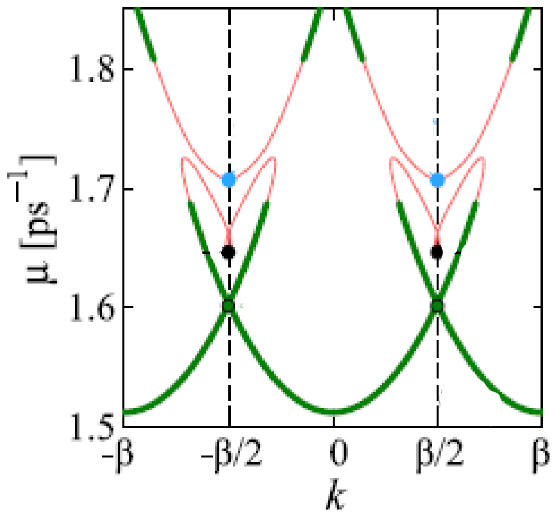




Nonlinear Bloch modes



Nonlinear dispersion relation

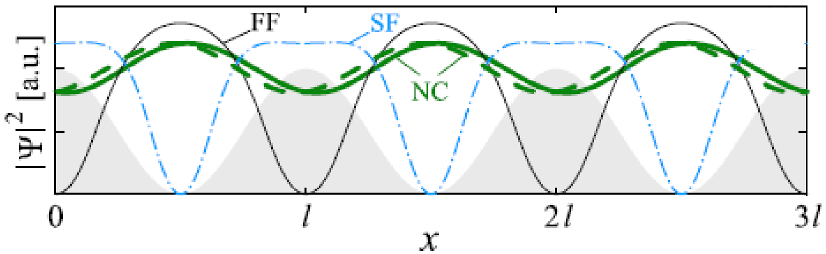
Loops,

'swallow' tails

Nonlinear Bloch waves

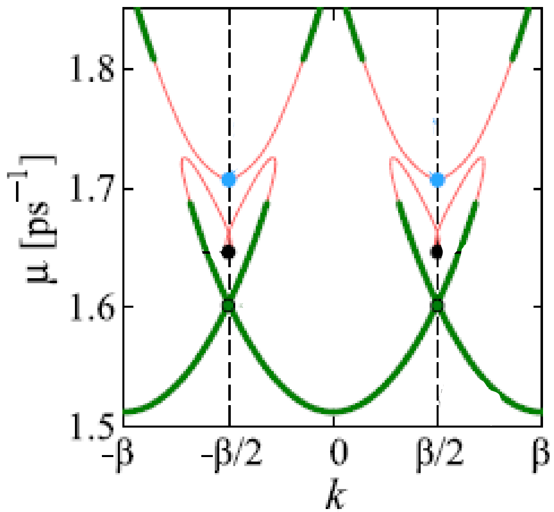
$$\psi(x,t) = \psi_{BM}(x;k) \cdot e^{-i\mu(k)t+ikx}$$

$$n(x,t) = f_{BM}(x;k)$$

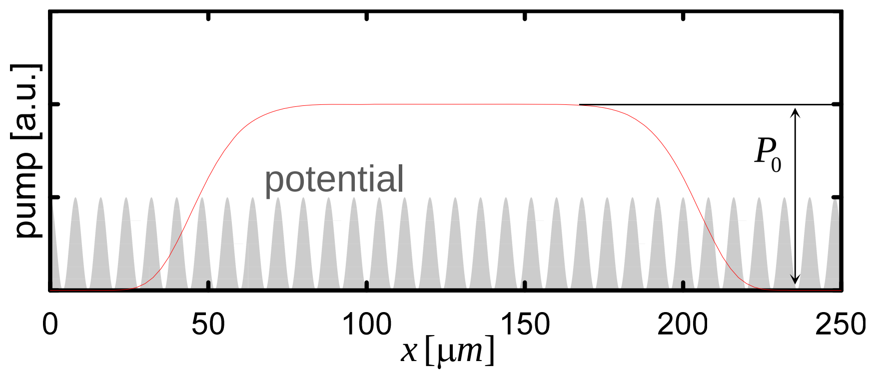


I. Yu. Chestnov et. al., Phys. Rev. B ***94****, 094306 (2016)*

Nonlinear Bloch modes



Nonlinear dispersion relation



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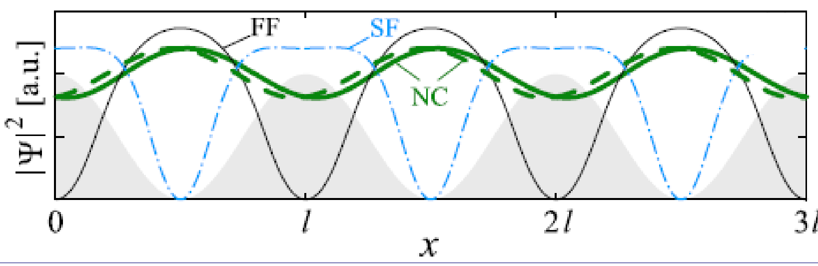
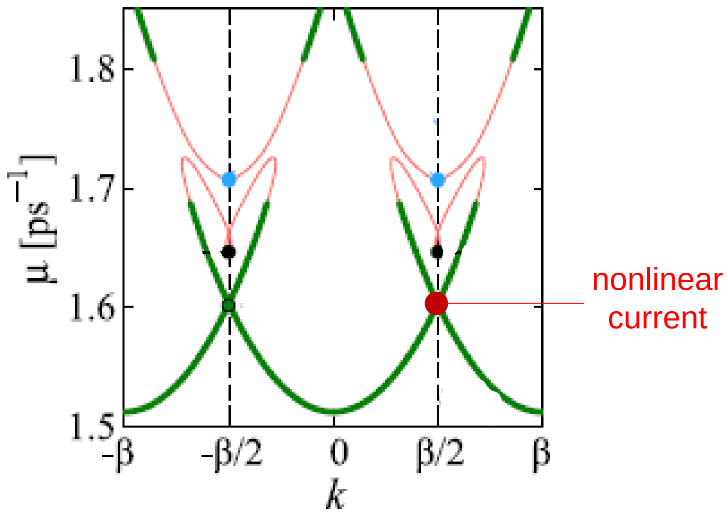
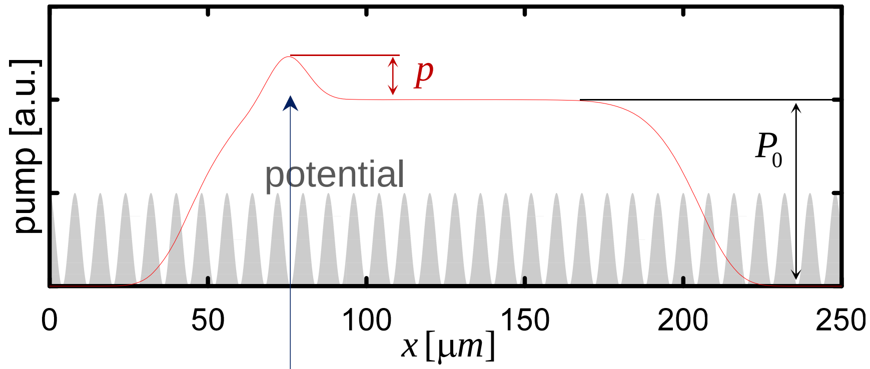


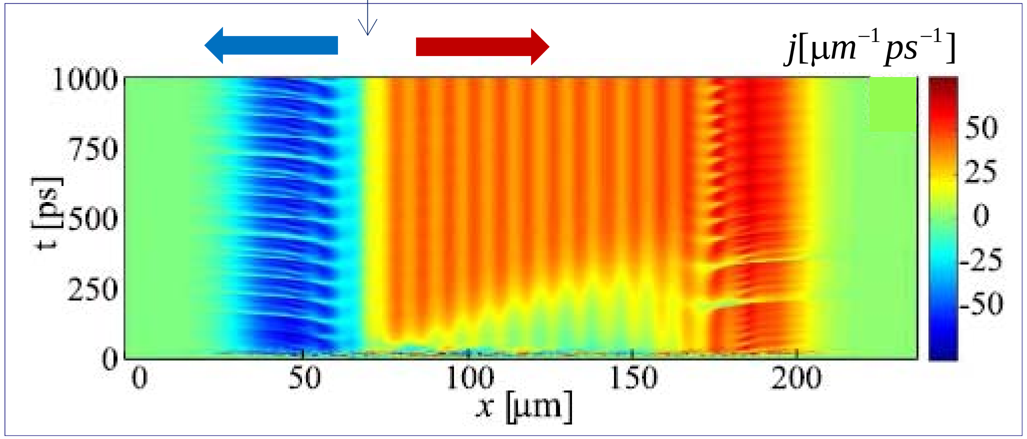
*I. Yu. Chestnov et. al., Phys. Rev. B **94**, 094306 (2016)*

Nonlinear Bloch modes – current states



Nonlinear dispersion relation





Nonlinear Bloch waves

- current at BZ edges

$$j(x,t) = \frac{i\hbar}{2m}\left(\frac{\partial \psi^*}{\partial x}\psi - \frac{\partial \psi}{\partial x}\psi^*\right)$$

*I. Yu. Chestnov et. al., Phys. Rev. B **94**, 094306 (2016)*

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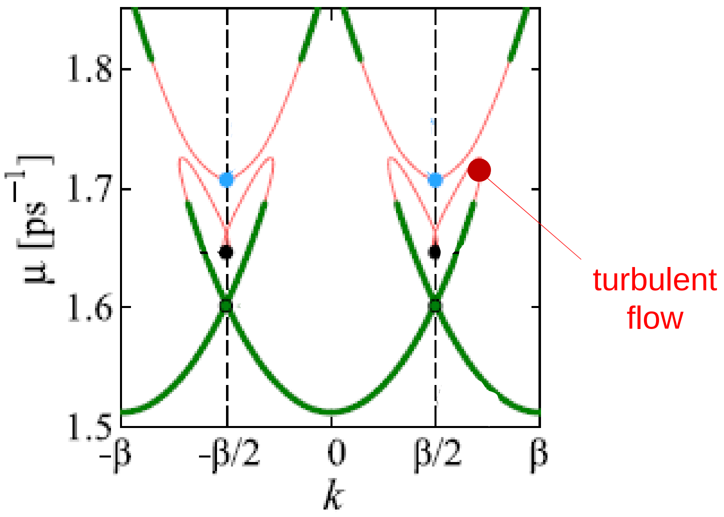
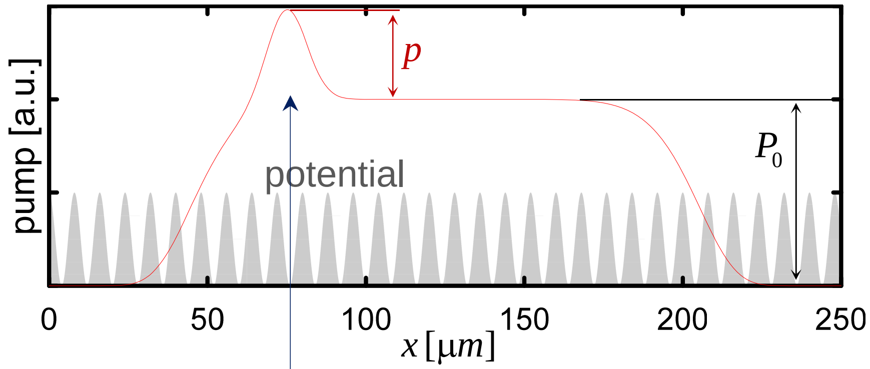
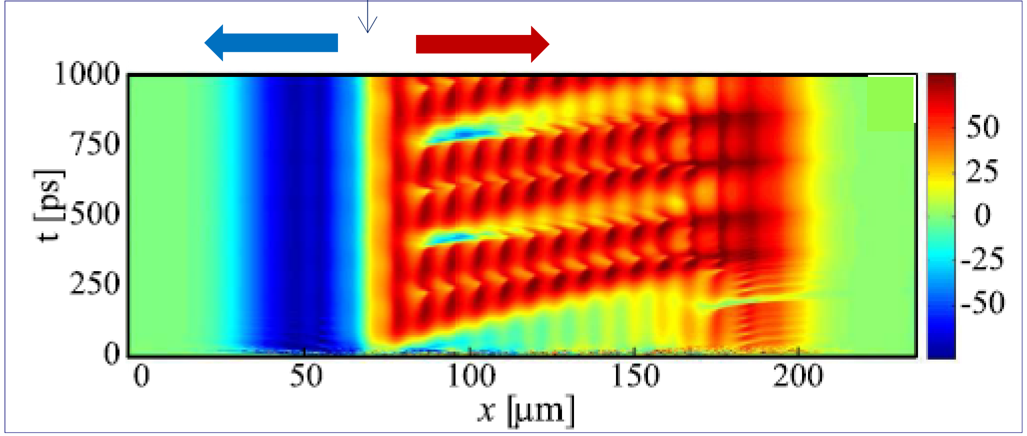


Nonlinear dispersion relation



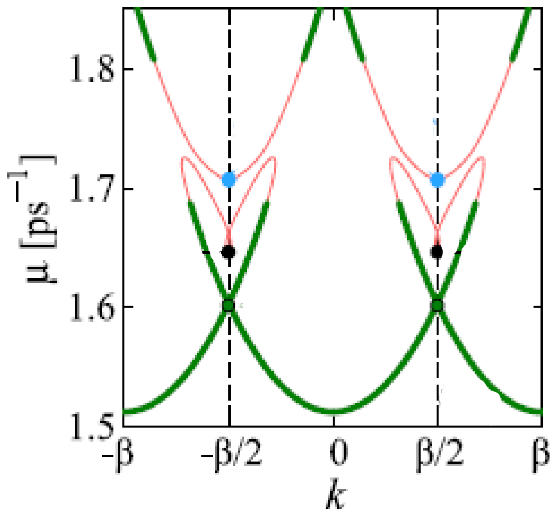


Nonlinear Bloch waves

- current at BZ edges
- turbulent flow

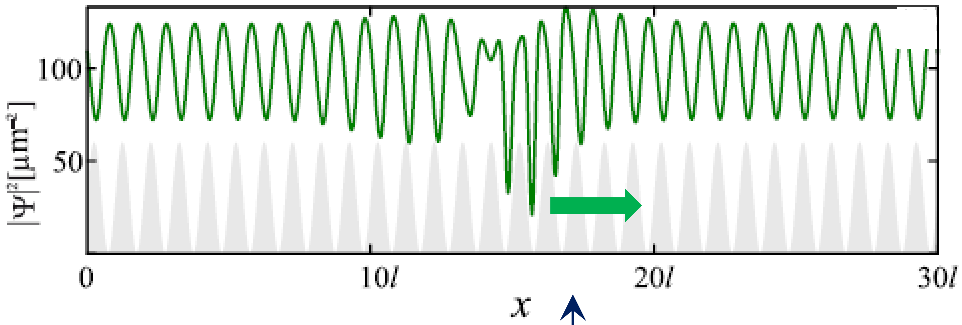
*I. Yu. Chestnov et. al., Phys. Rev. B **94**, 094306 (2016)*

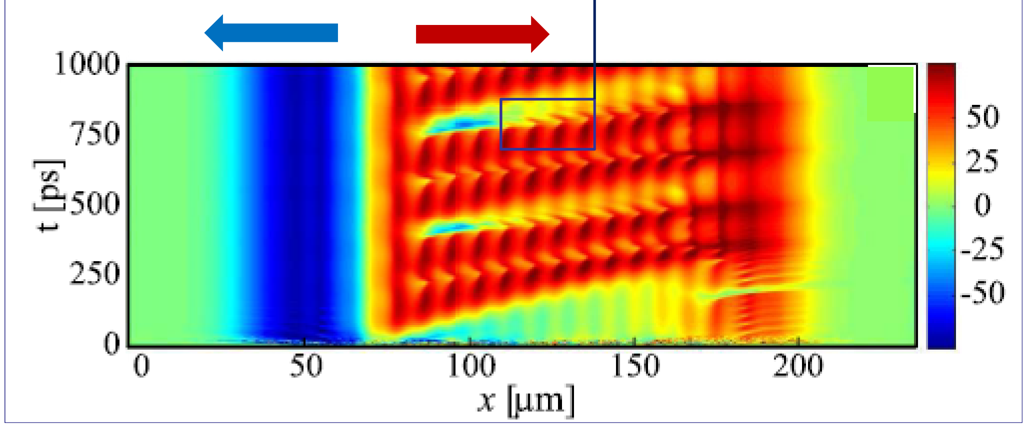
Nonlinear Bloch modes – current states



Nonlinear dispersion relation

Soliton profile





Nonlinear Bloch waves

- current at BZ edges
- turbulent flow, soliton emission

I. Yu. Chestnov et. al., Phys. Rev. B ***94****, 094306 (2016)*

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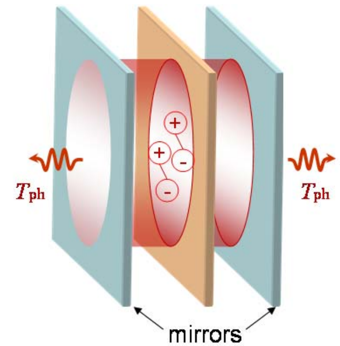

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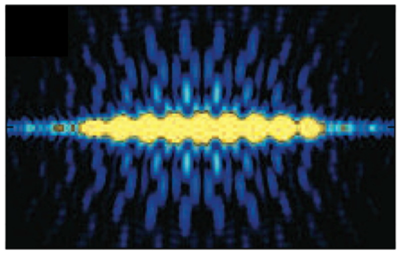
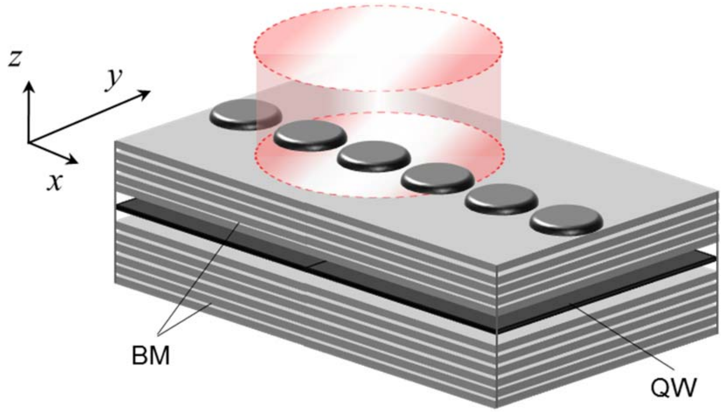
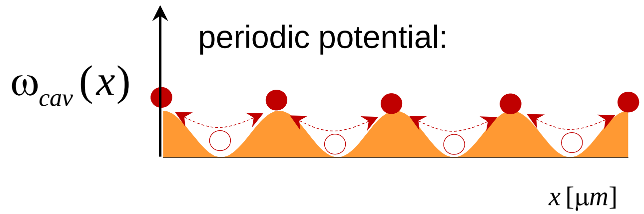
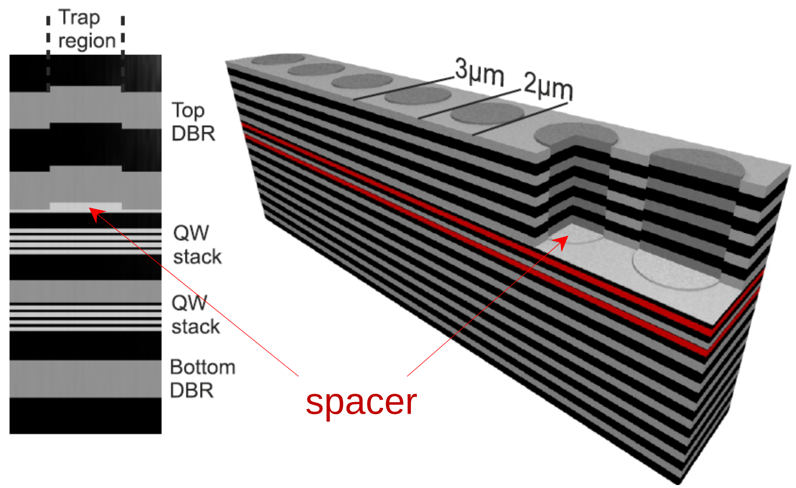




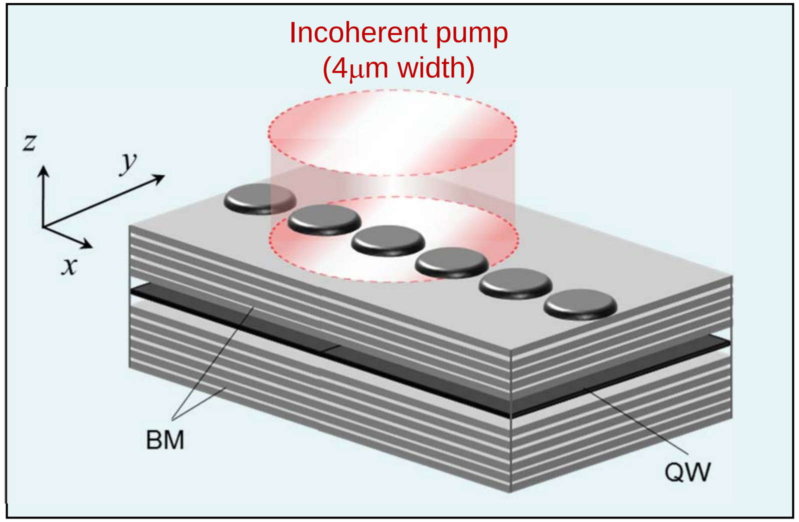


K. Winkler, *et al.*, "Collective state transitions of exciton-polaritons loaded into a periodic potential," PRB **93**, 121303(R) (2015)

Chain of coupled trapping potentials (GaAs/ AlGaAs)

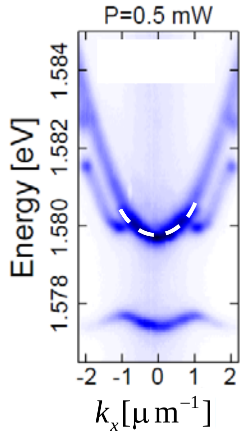


Chain of potentials – photoluminescence



K. Winkler, *et al.*, PRB **93**, 121303(R) (2015)

Experiment:



Photoluminescence

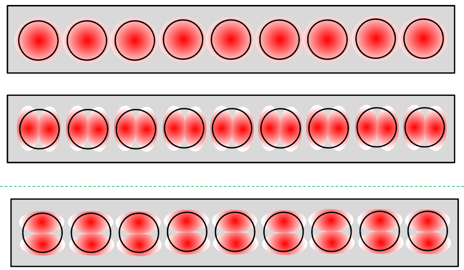
- spontaneous emission

Bloch modes

1st band

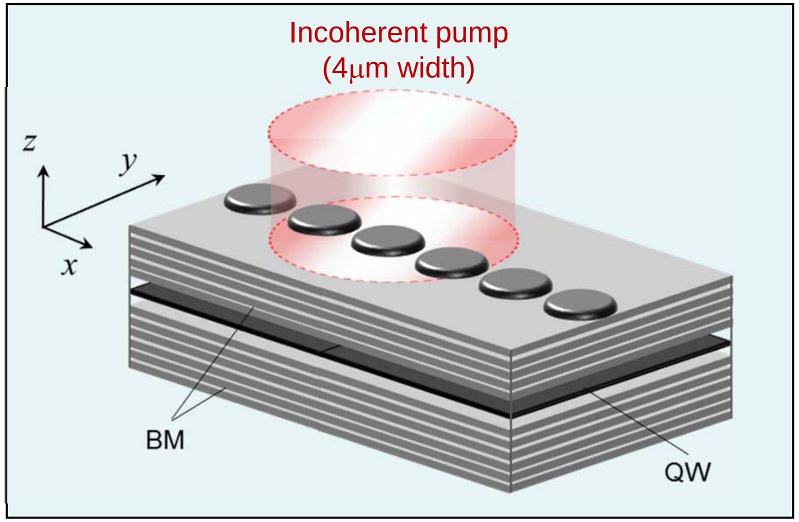
2nd band

“transverse” band



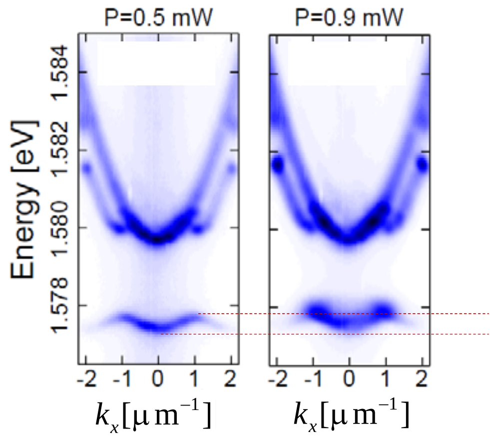
Chain of potentials – photoluminescence

Julius-Maximilians-
UNIVERSITÄT
WÜRZBURG



K. Winkler, *et al.*, PRB **93**, 121303(R) (2015)

Experiment:

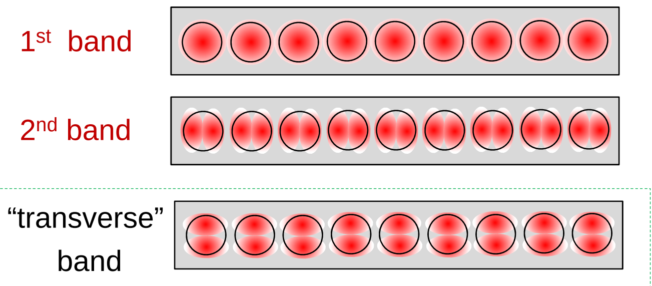


Below threshold

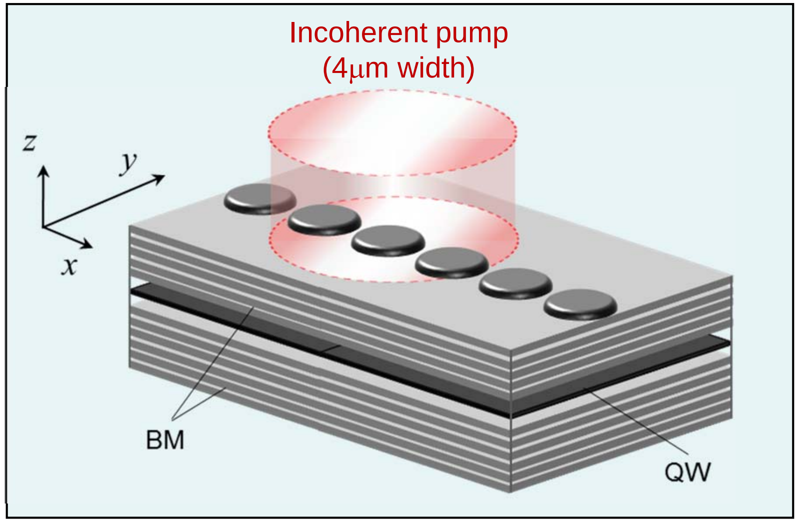
Photoluminescence

- spontaneous emission
- many-body effects (blue shift)

Bloch modes

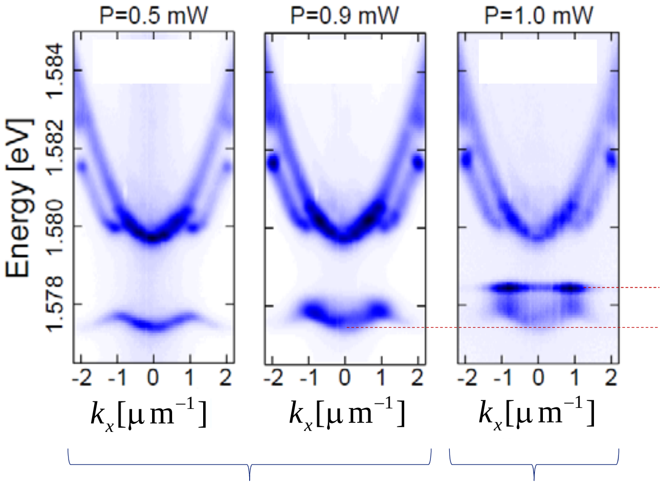


Chain of potentials – photoluminescence



K. Winkler, *et al.*, PRB **93**, 121303(R) (2015)

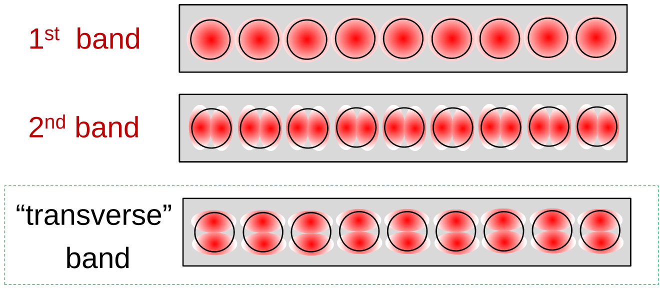
Experiment:



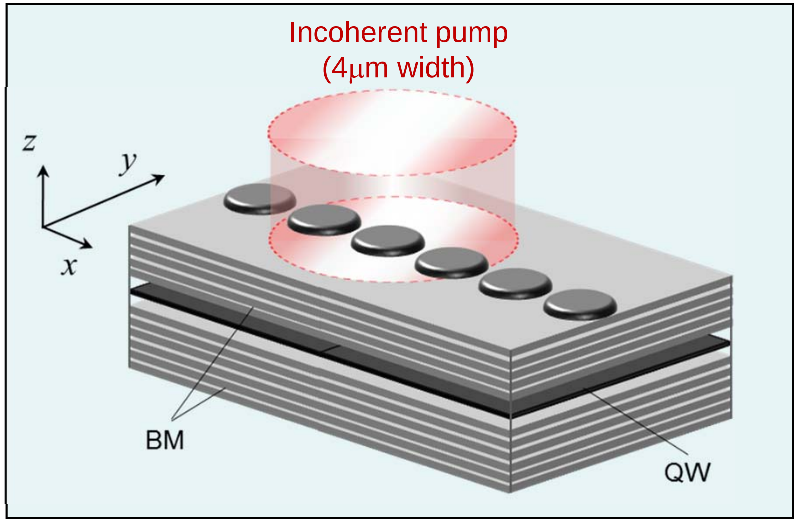
Photoluminescence

- spontaneous emission
- many-body effects (blue shift)
- stimulated scattering

Bloch modes

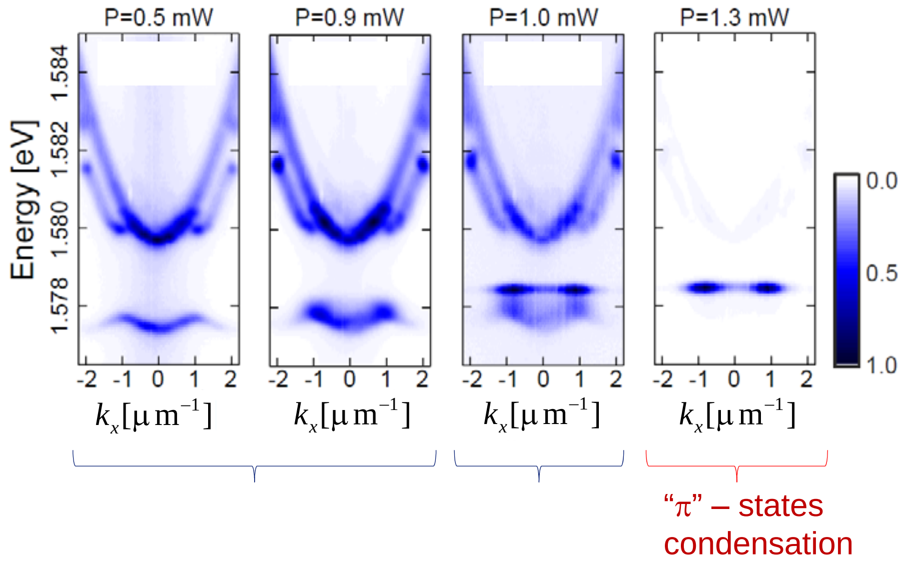


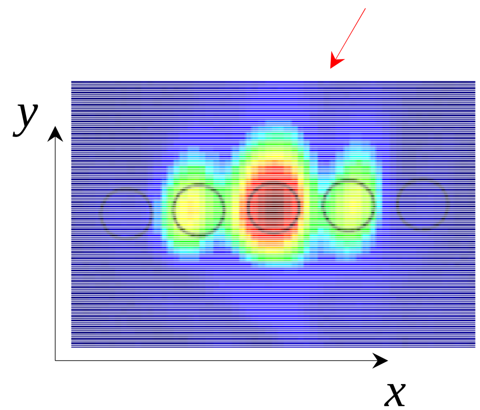
Chain of potentials – photoluminescence



K. Winkler, *et al.*, PRB **93**, 121303(R) (2015)

Experiment:

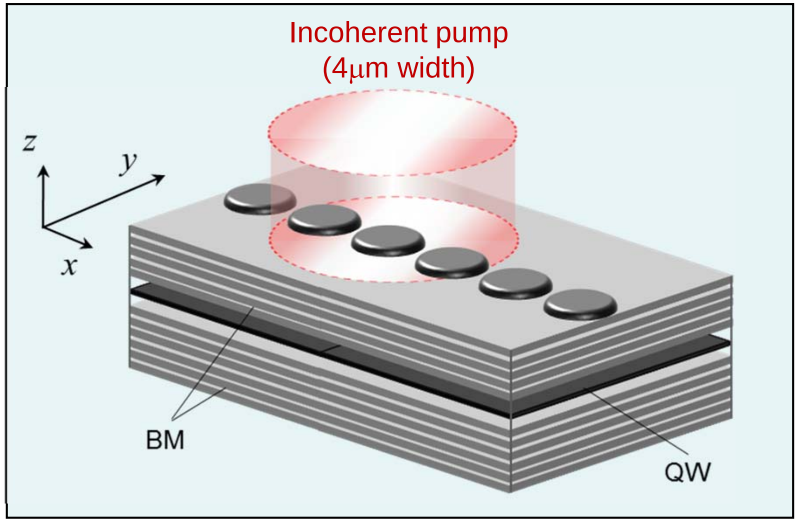




Photoluminescence

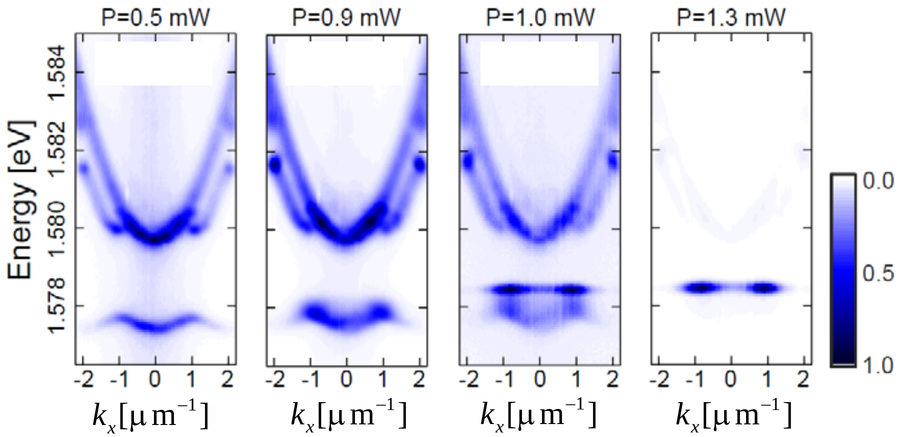
- spontaneous emission
- many-body effects (blue shift)
- stimulated scattering
- spatial and temporal coherence

Chain of potentials – theory

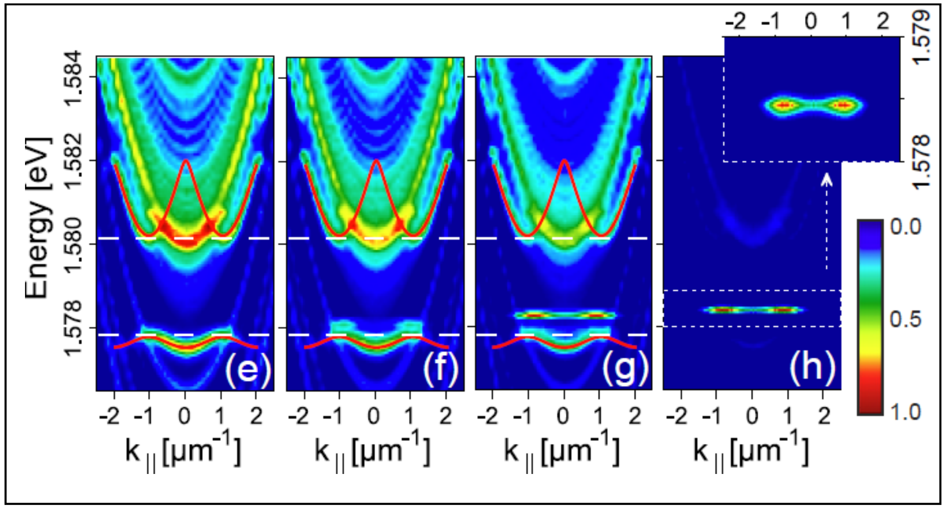


K. Winkler, *et al.*, PRB **93**, 121303(R) (2015)

Experiment:



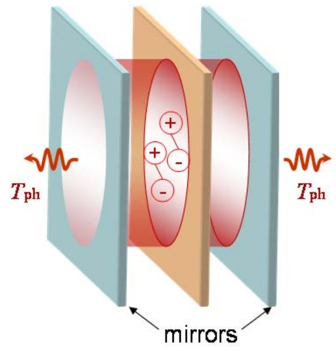
Monte Carlo simulations of Gross-Pitaevskii model with stochastic variables



Outline

✓ Introduction

- *strong light-matter coupling*
- *exciton-polaritons in photonic lattices*

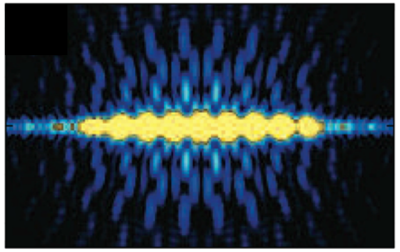


✓ Exciton-polaritons in 1D weak-contrast lattices

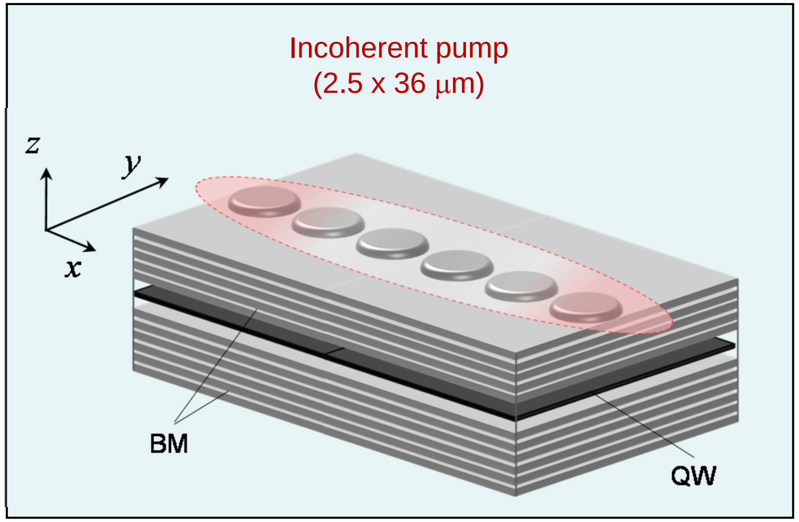
- *π -state oscillations*
- *nonlinear Bloch-Modes*

✓ Controlled loading into chain of coupled mesas

- *chain of coupled mesas*
- *emission from higher Bloch modes*
- *Talbot patterns*

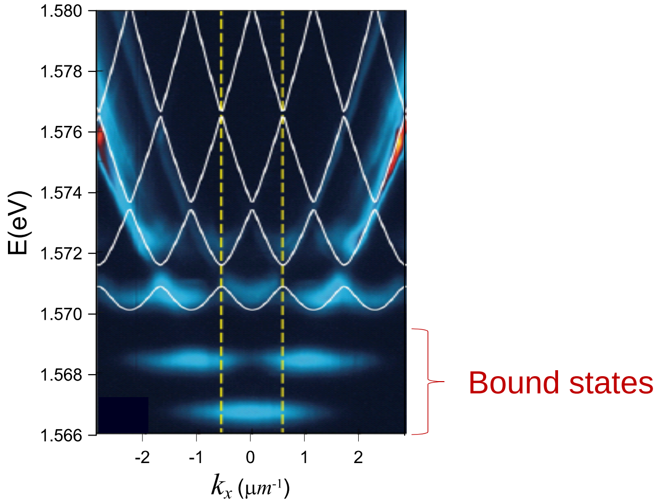


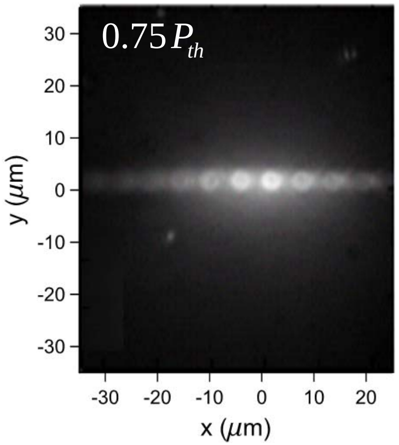
Chain of potentials – Bloch modes



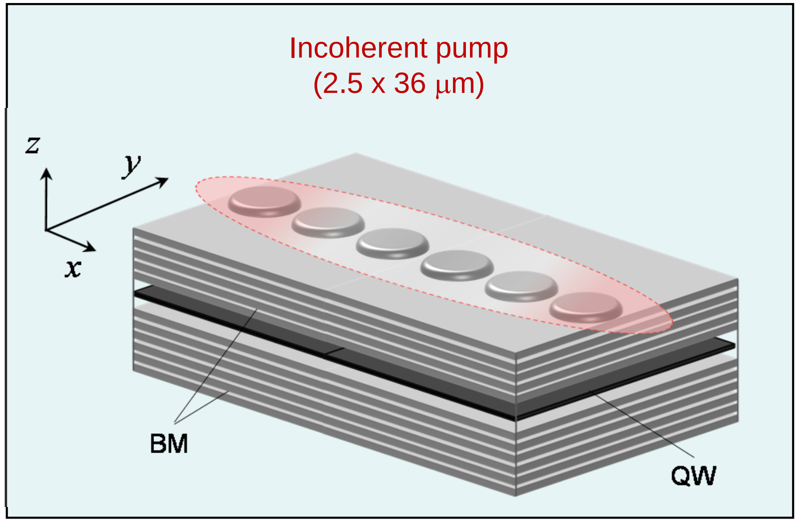
T. Gao, *et al.*, PRL **117**, 097403 (2016)

below threshold





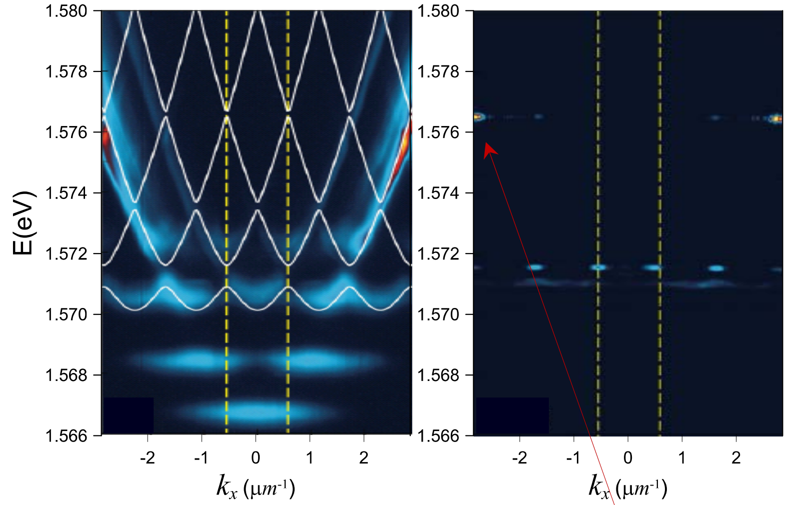
Chain of potentials – Bloch modes

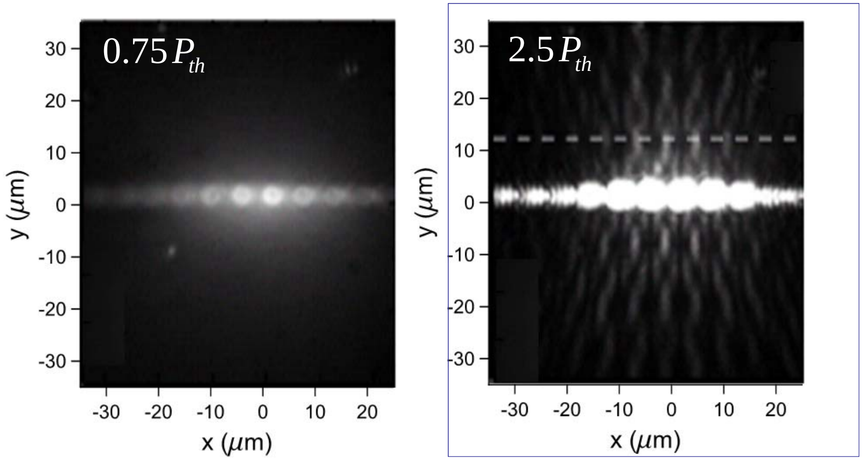


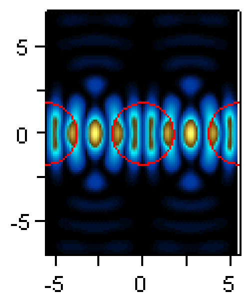
T. Gao, *et al.*, PRL **117**, 097403 (2016)

below threshold

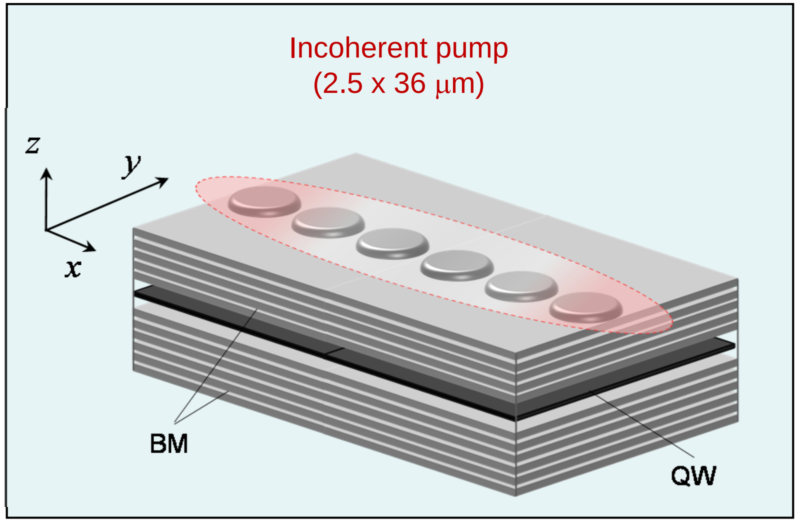
above threshold







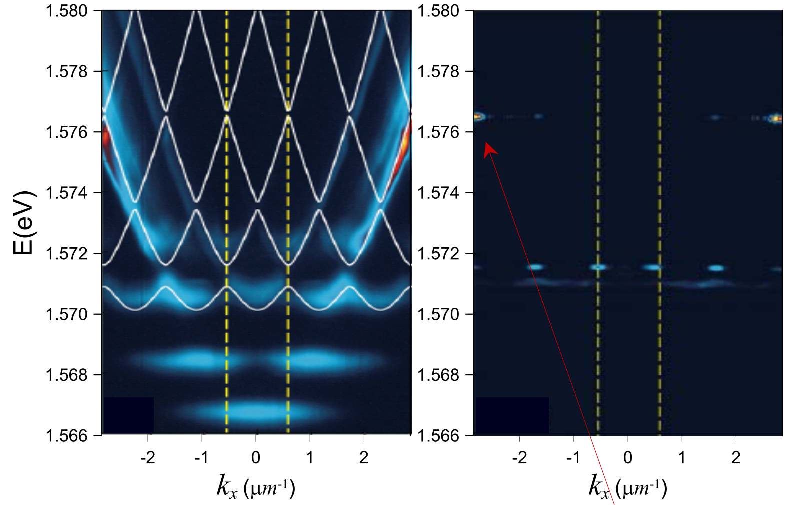
Chain of potentials – Bloch modes

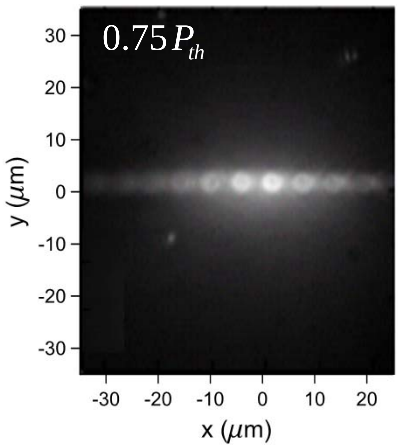


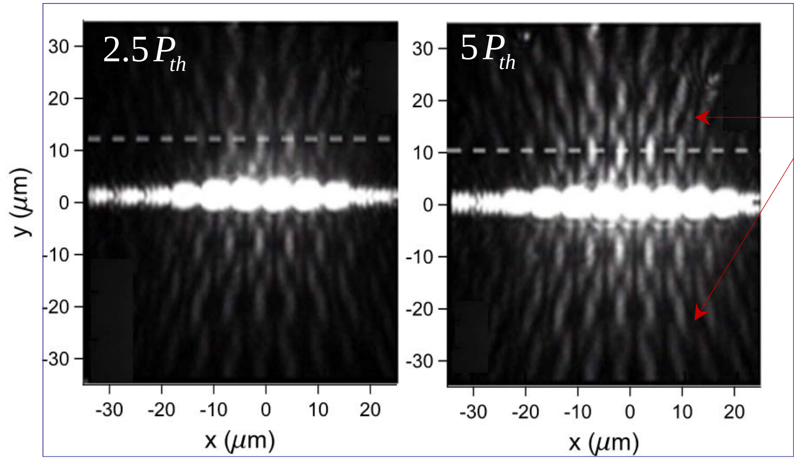
T. Gao, *et al.*, PRL **117**, 097403 (2016)

below threshold

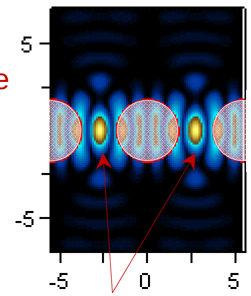
above threshold







Radiation in plane
of the cavity
(Talbot patterns)



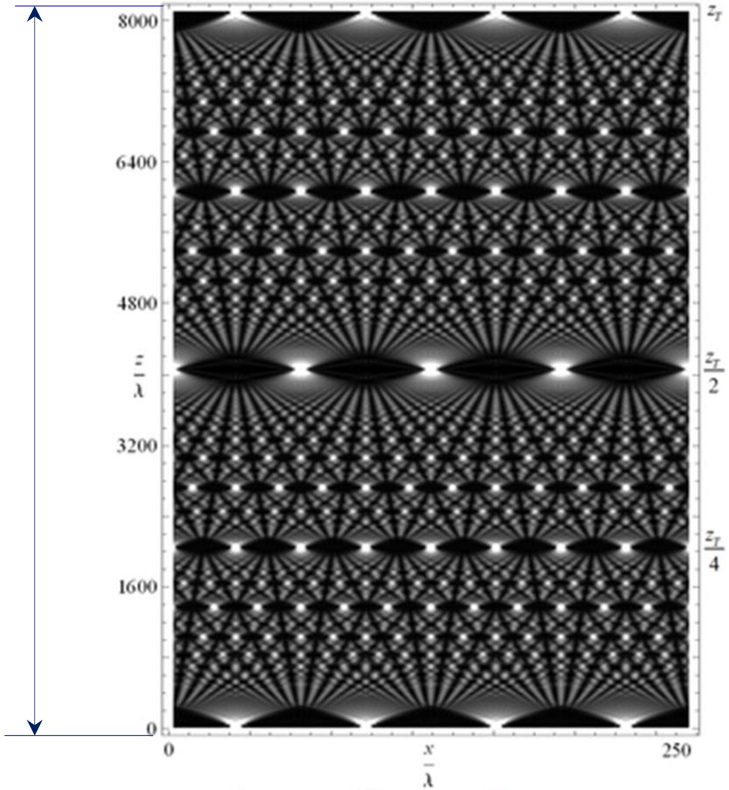
Peaks outside
potentials
(out of phase)

Chain of potentials – Talbot effect

William Henry Fox Talbot
(1800 – 1877)

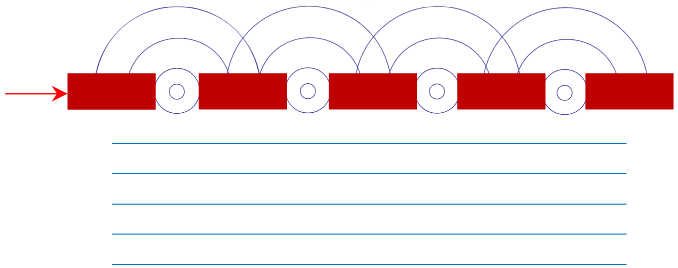
Talbot length:

$$z_T = \frac{\lambda}{1-\sqrt{1-\frac{\lambda^2}{l^2}}}$$



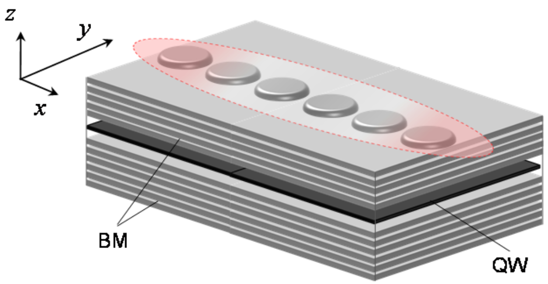
Talbot effect –
near-field (Fresnel)
diffraction effect
(observed in 1836)

diffraction grating



plane wave

Chain of potentials – Talbot effect



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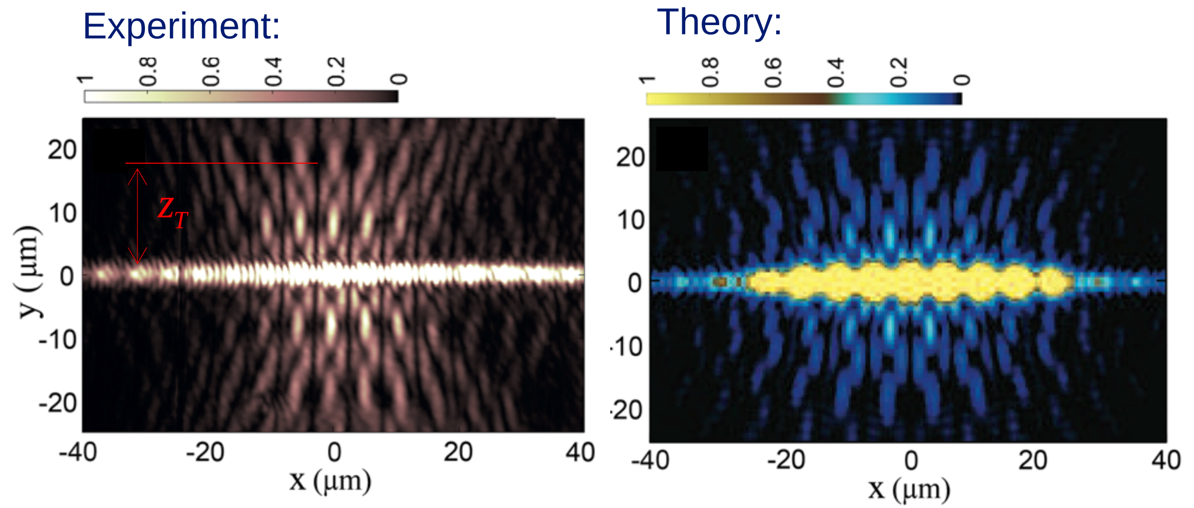
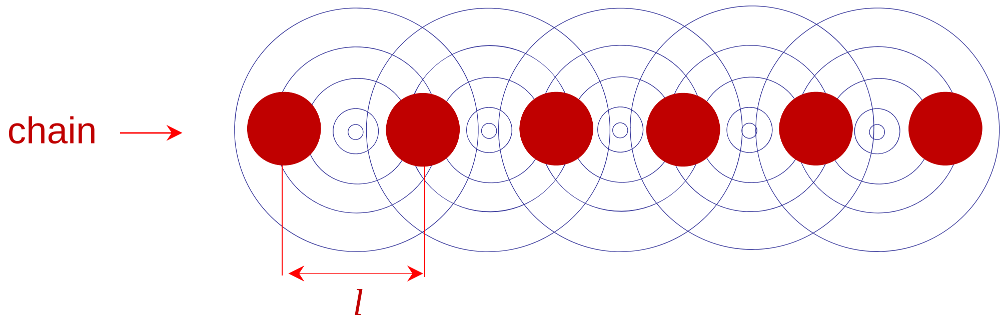


Talbot length:

$$z_T = \frac{\lambda_p}{1 - \sqrt{1 - \frac{\lambda_p^2}{l^2}}}$$



Conclusions

- Process of spontaneous coherence formation of exciton-polaritons can be actively controlled by periodic structures

- Nonlinear superposition of Bloch modes may result in macroscopic oscillations or nonlinear current states

- Controlled loading of the exciton-polaritons into different Bloch states has been demonstrated

- An interference between higher Bloch modes and free-propagating exciton-polaritons may results in formation of Talbot patterns

-Thank you ! -