Polariton dynamics in planar microcavities: The effect of cross-hatch disorder

Wolfgang Langbein[1], Vincenzo Savona[2], Dirk Reuter[3], Andreas D. Wieck[3]

[1]School of Physics and Astronomy, Cardiff University, Cardiff CF24 3AA, United Kingdom, Email: langbeinww@cf.ac.uk [2]Institut de Théorie des Phénomènes Physiques, EPFL, CH-1015 Lausanne, Switzerland
[3]Angewandte Festkörperphysik, Ruhr-Universität Bochum, 44780 Bochum, Germany

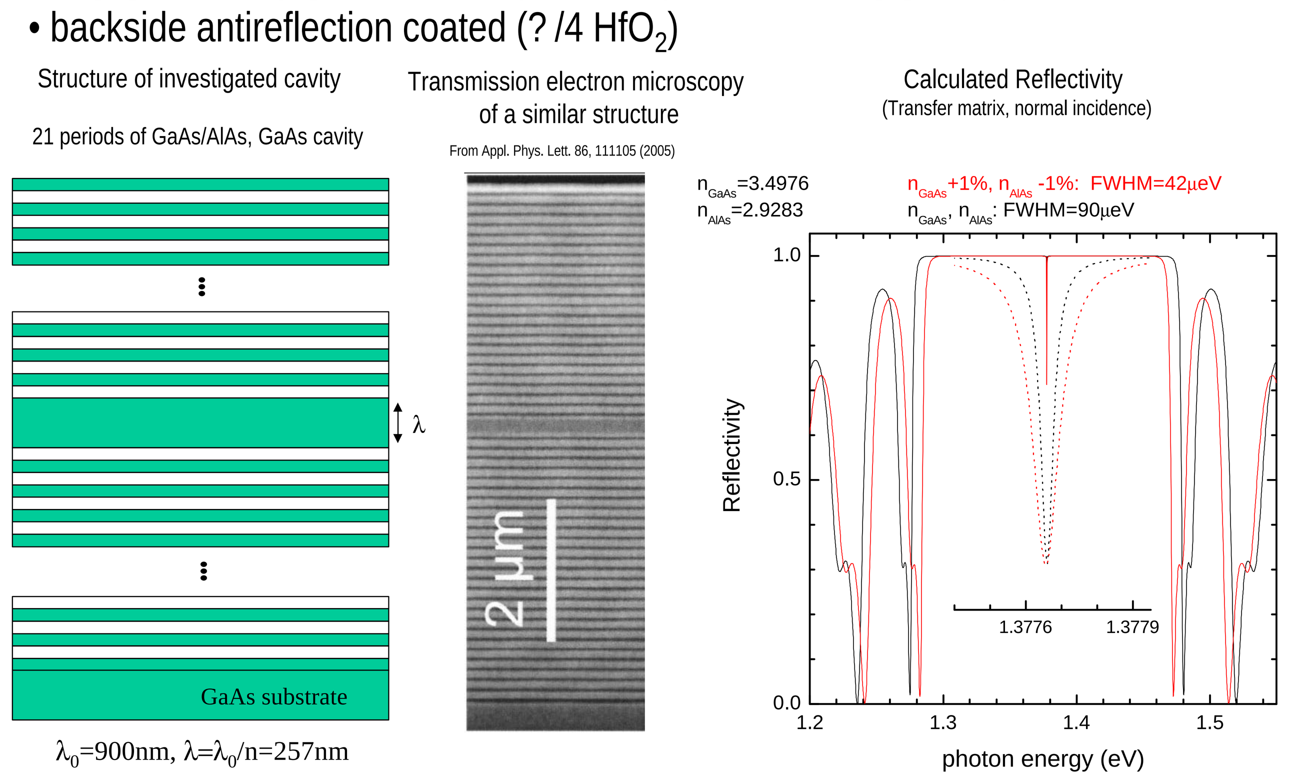
Introduction

Planar semiconductor microcavities create a confined light mode in one direction by Bragg reflectors, while the in-plane motion of the light is free in ideal structures. The Bragg reflectors can be designed to a reflection coefficient arbitrarily close to unity, in which case the properties of the light modes are dominated by in-plane disorder, which determines the cavity linewidth measured, both for the inhomogeneous broadening and the homogeneous broadening of the modes

We have investigated this in-plane disorder on an empty microcavity of a high Bragg reflectivity, and identify the cross-hatch dislocation pattern formed due to the lattice mismatch as main disorder mechanism.

Microcavity structure

- grown by molecular beam epitaxy (MBE)
- 21 period GaAs/AlAs Bragg mirrors
- 1 ? GaAs cavity
- resonant wavelength 900nm at low temperatures
- negligible cavity gradient <100µeV/mm (rotation during growth)
- backside antireflection coated (? /4 HfO_2)

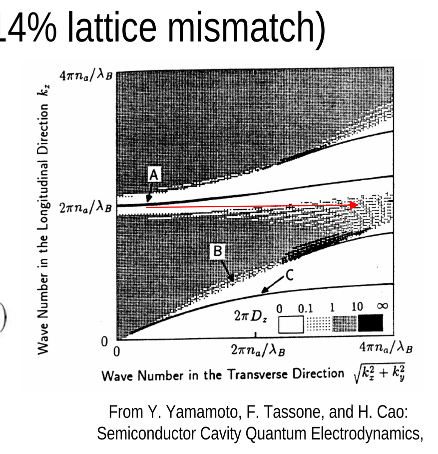


- predicted cavity linewidth 90µeV for nominal refractive indices of GaAs 3.498 and AlAs 2.928 (at 900nm, 4K, J. Appl. Phys. **87**, 7825)
- Measured linewidth down to 45µeV
- within 1% accuracy of the refractive indices, minimum predicted linewidth 42µeV: negligible effect of intrinsic absorption and scattering
- Confirmed by Reitzenstein et al, Appl. Phys. Lett. **90**, 251109 (2007): linewidth of 8µeV observed in >30 pair Bragg AlAs/GaAs micropillars

Theoretical Model

- Polariton properties dominated by long-range in-plane disorder, created by misfit dislocation in the strained AlAs/GaAs system (0.14% lattice mismatch)
- 2D particles with finite mass, with effective potential V(**R**)
- Position dependent damping γ(**R**) due to scattering into lossy photon modes
- 2D Schrödinger equation for the polariton polarization

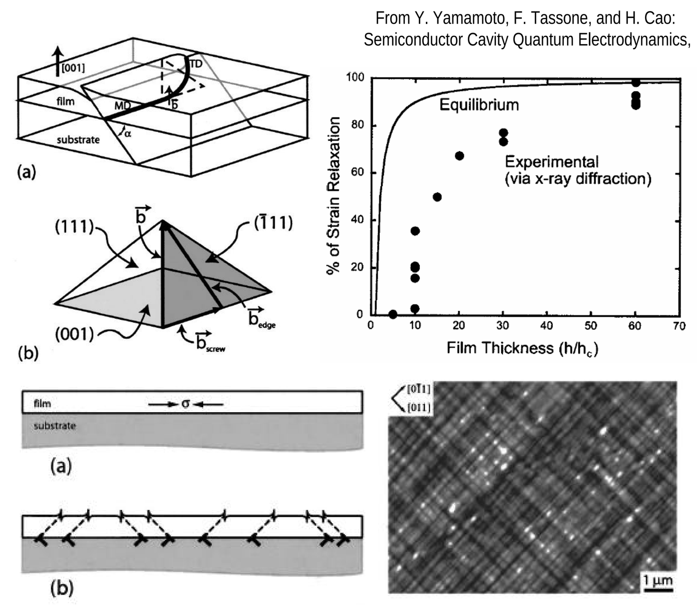
$$-i\hbar\frac{\partial P(\mathbf{R},t)}{\partial t}=\left(-\frac{\hbar^2}{2M}\nabla^2+V(\mathbf{R})+i\gamma(\mathbf{R})\right)P(\mathbf{R},t)+\mu E_{in}(\mathbf{R},t)$$



From Y. Yamamoto, F. Tassone, and H. Cao: Semiconductor Cavity Quantum Electrodynamics,

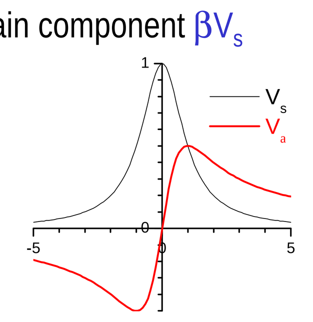
Potential Model:

- Potential created by superposition of infinitely extended hatches along {110}
- Hatch density different in [110] and [1$\bar{1}$0]
- Hatch potential is superposition of
  - Asymmetric surface modulation αV_a
  - Symmetric strain component βV_s



$$V_a(r)=\frac{rr_0}{r_0^2+r^2}$$

$$V_s(r)=\frac{1}{1+r^2/r_0^2}$$



Figures from J. Appl. Phys. **91**, 1935

$$V_x=a\left(\sum_{j=1}^{n_x}e_{xj}V_a(x-x_j)+\sum_{j=1}^{n_y}e_{yj}V_a(y-y_k)\right)+\sum_{j=1}^{n_x}b_\perp V_s(x-x_j)+\sum_{j=1}^{n_y}b_\parallel V_s(y-y_j)$$

V_y : exchanging x & y

Asymmetric surface modulation — Symmetric strain modulation, birefringent

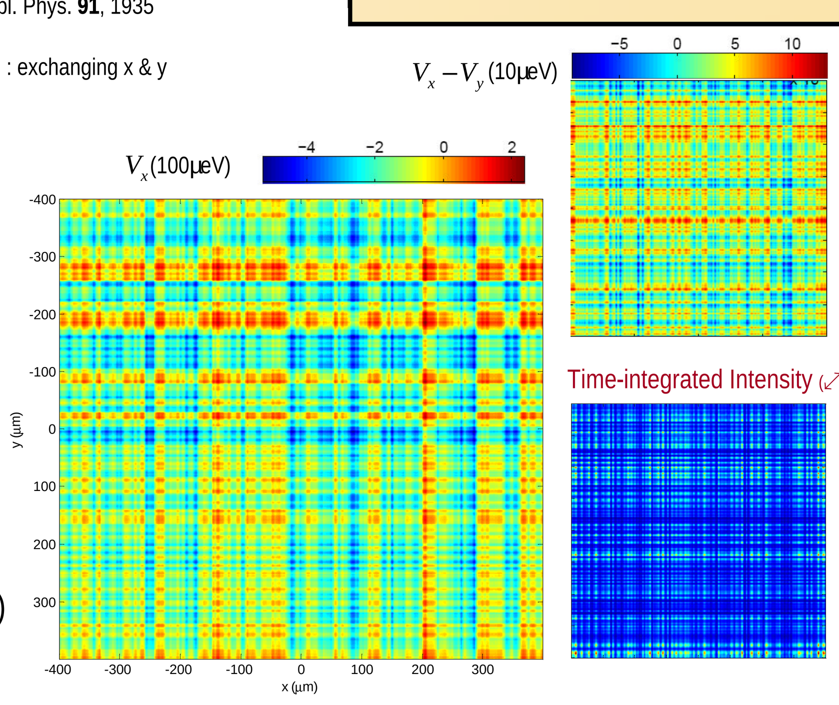
$$g_x=g_0+g_h\left\{\left(1+\frac{b_\perp^2}{a^2}\right)\sum_{j=1}^{n_x}V_s(x-x_j)+\left(1+\frac{b_\parallel^2}{a^2}\right)\sum_{j=1}^{n_y}V_s(y-y_j)\right\}$$

g_y : exchanging x & y

- Hatch positions x_j, y_i *and polarity sign* e_i created sequentially using Monte-Carlo Metropolis, with repulsive interaction between hatches (autocorrelation of strain relaxation)

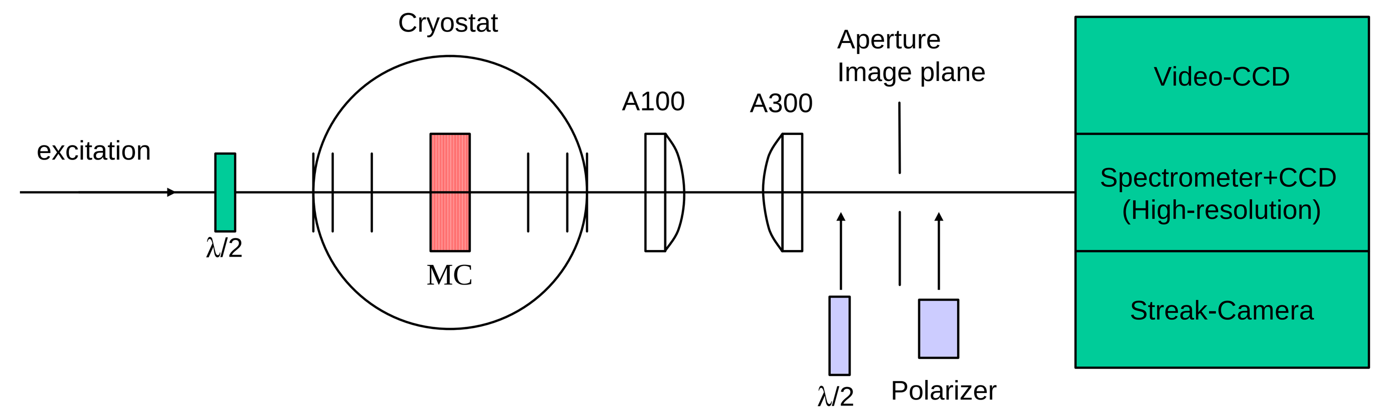
Simulations for the parameters:

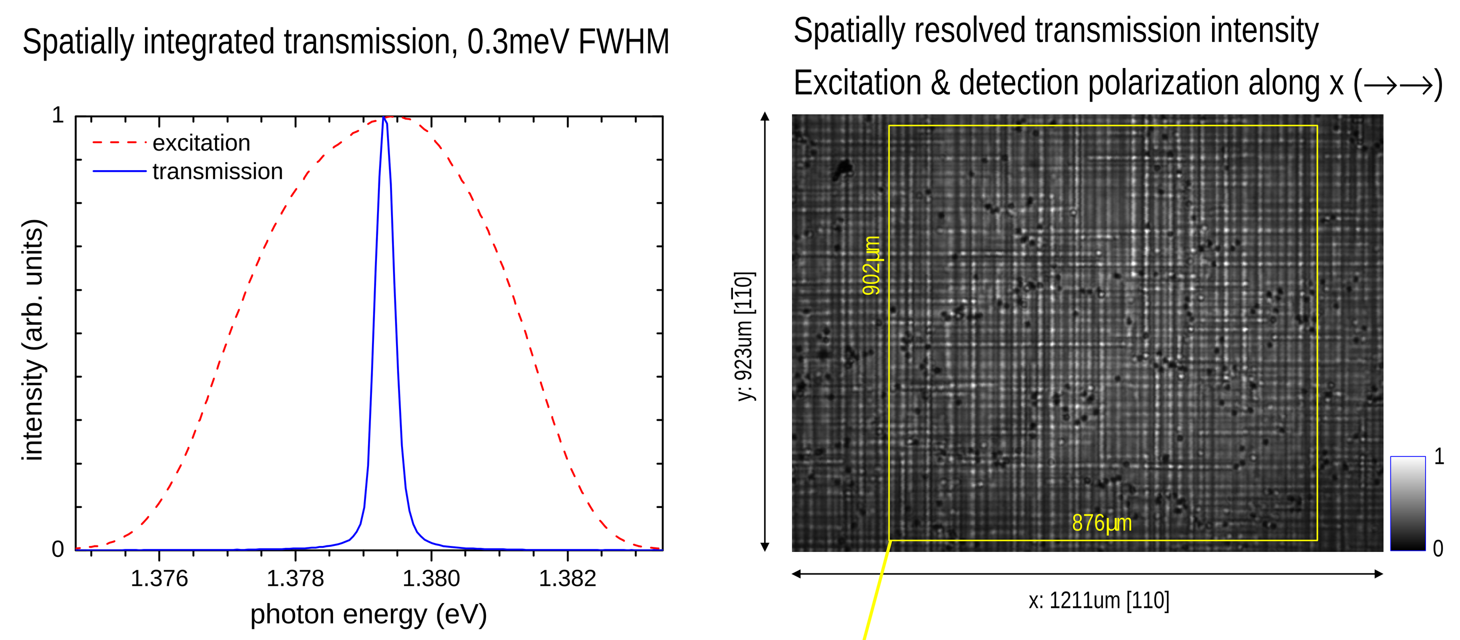
- α=60µeV, $\beta_\perp$=-35µeV, $\beta_\parallel$=-15µeV, n_x=300, n_y=200, r_0=3.11µm, T_{eff}=10
- M=3.5·10^{-5} m_e, 1ps pulse at normal incidence, diagonal polarization (⤢)
- 800µmx800µm, 1024x1024 grid points



Experiment: Time & spectrally resolved transmission imaging

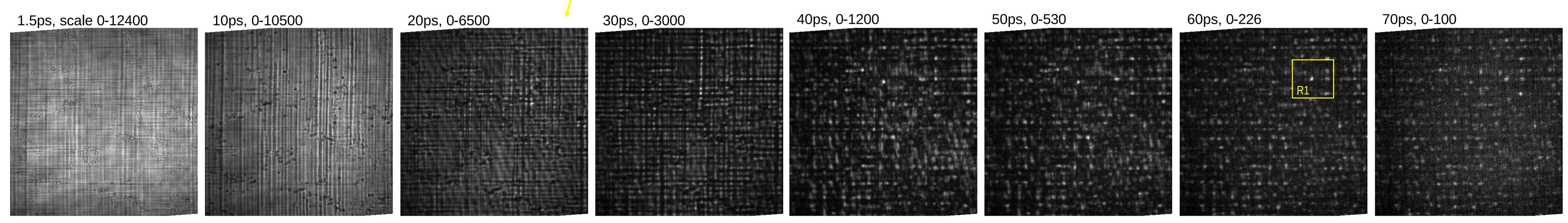
- sample in helium cryostat at 10K
- excitation from substrate side at normal incidence
- spot size ~1mm
- 500fs laser pulses (3.9meV FWHM) centred to the cavity resonance





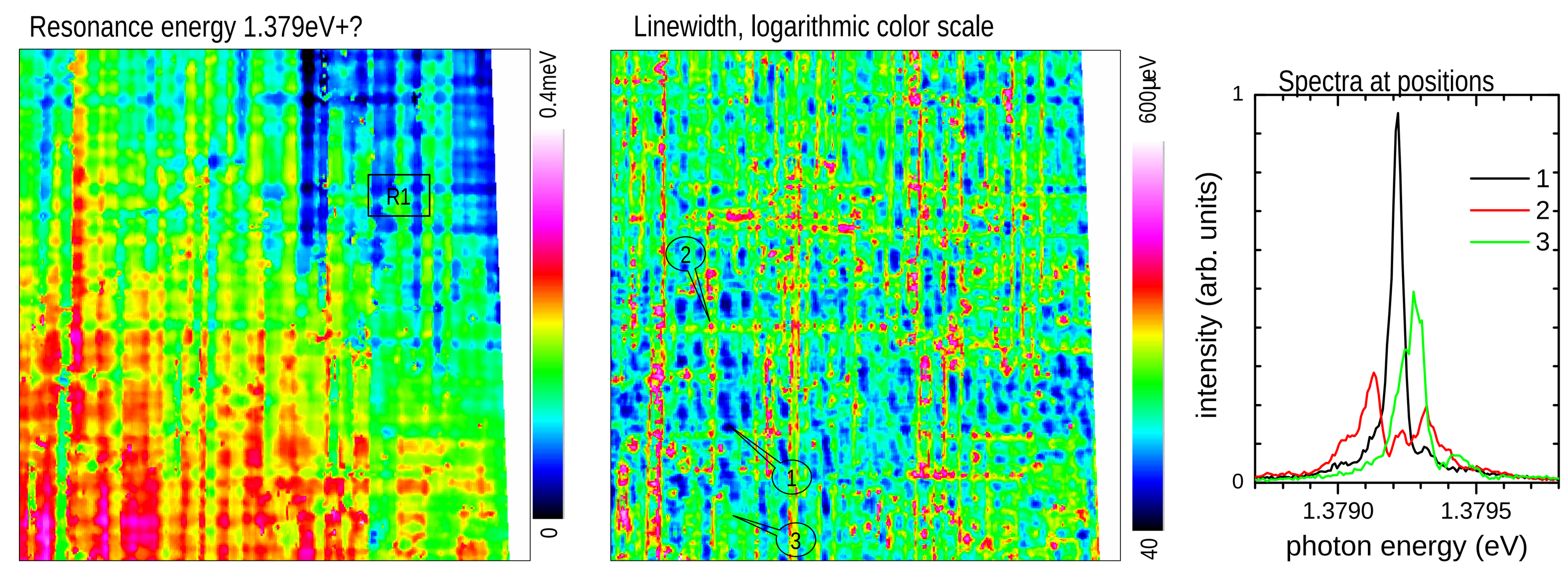
- excitation spot envelope visible
- structure dominated by stripes along [110], [1$\bar{1}$0]
- stripe length ~1mm, shorter in [110] direction
- stripe density less in [110] direction
- additional point-like structures, density 2·10^4/cm^2
- Origin of structure seem to be dislocations:
  - Lines made by misfit dislocations
  - points made by pure threading dislocations ?

Time-resolved transmission intensity imaging (→→)



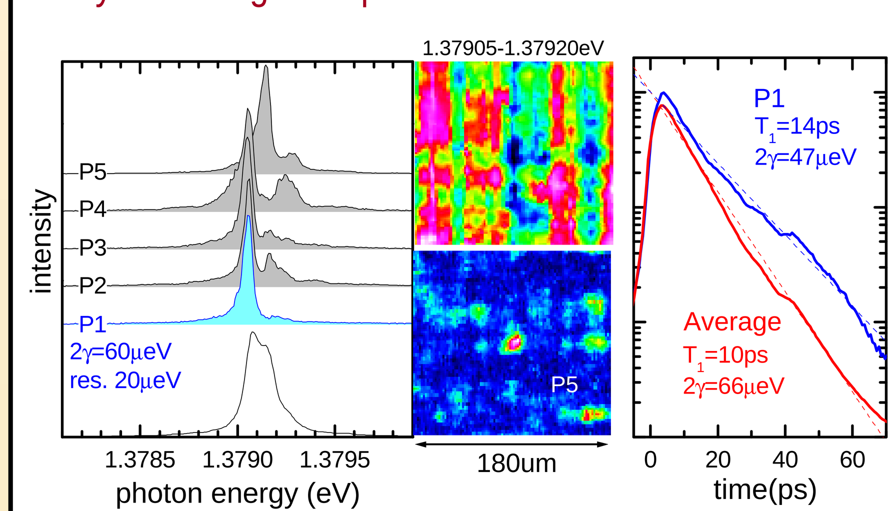
- initially homogeneous transmission: spatial structure due to in-plane polariton dynamics, as opposed to structured mirror transmissivity
- for long times polaritons "localize", i.e. the lifetime of these localized polariton states is longest

Spectrally resolved intensity imaging (→→)



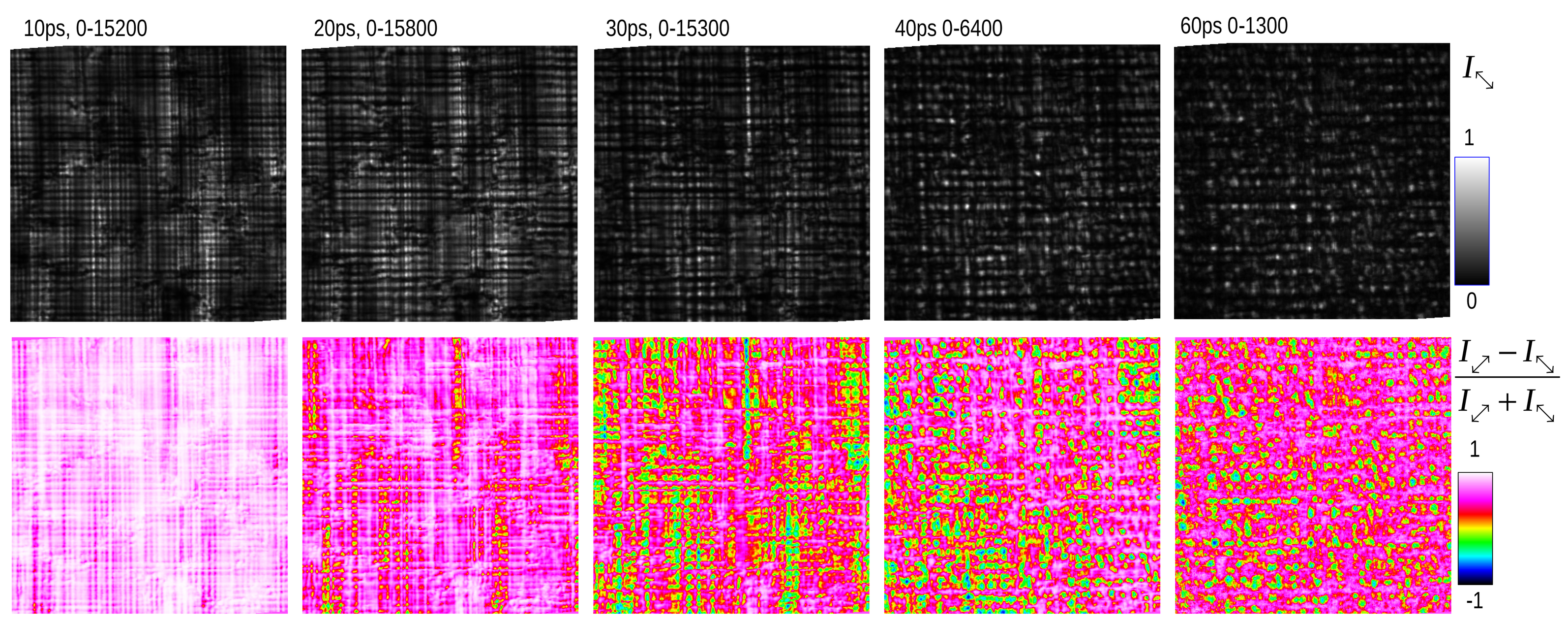
- spatially inhomogeneous distribution of resonance energy and width
- small overall gradient of energy ~100µeV/mm due to thickness gradient (10^{-4}/mm)
- linewidths down to 45µeV, below nominal cavity linewidth (20µeV resolution)

Analysis of long-lived polariton state



- Selected spot of long temporal decay shows extended average decay time
- Local emission spectrum linewidth in agreement with increased decay time
- Spectra al all long-lived spots have narrorw linewidth
- localized polariton states form in a local minimum of the energy landscape

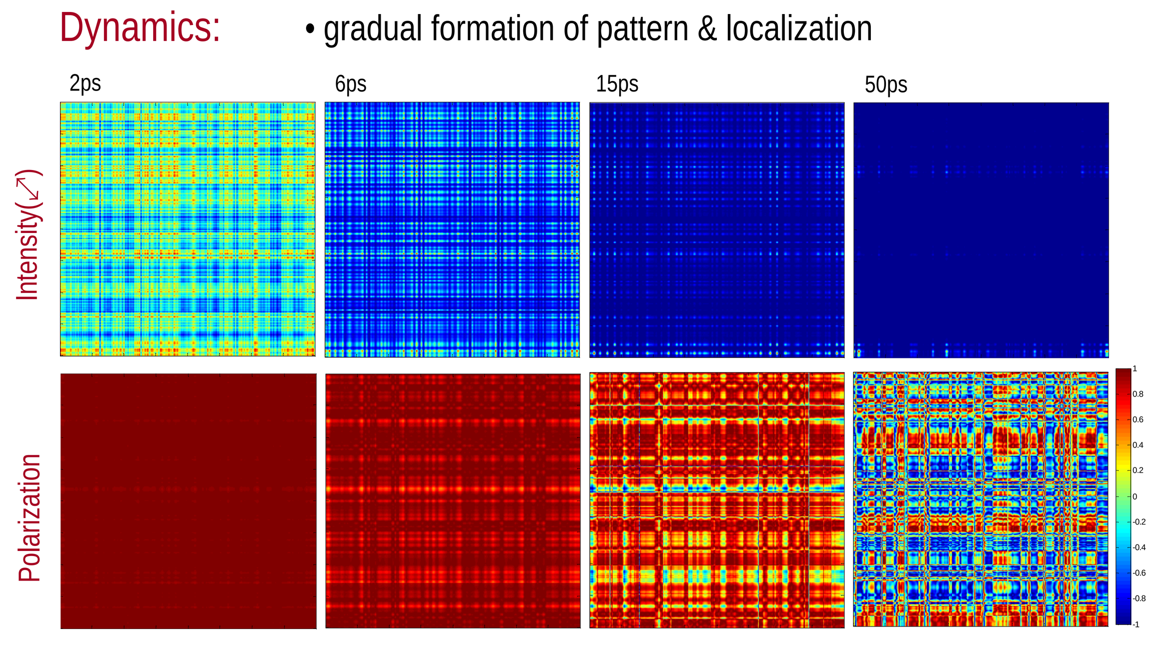
Polarization dynamics: Only significant for light polarizations diagonal to {110}: Cavity birefringence has crystal axis symmetry. Data for ⤢ excitation



- long-range distribution of birefringence: related to anisotropic strain relaxation: more misfit-dislocations along [110] than [1$\bar{1}$0]
- strong birefringence local to stripes: strong anisotropy of local in/plane strain
- Polarization randomized after long time

Dynamics:

- gradual formation of pattern & localization



Spectra:

- cuts along x, ⤢ and ⤡ polarized
- spatial structure of energy and linewidth