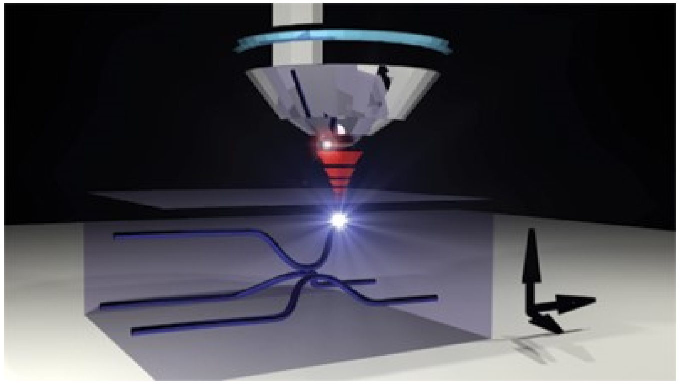
Coherent diffusive photonics and the photon gun



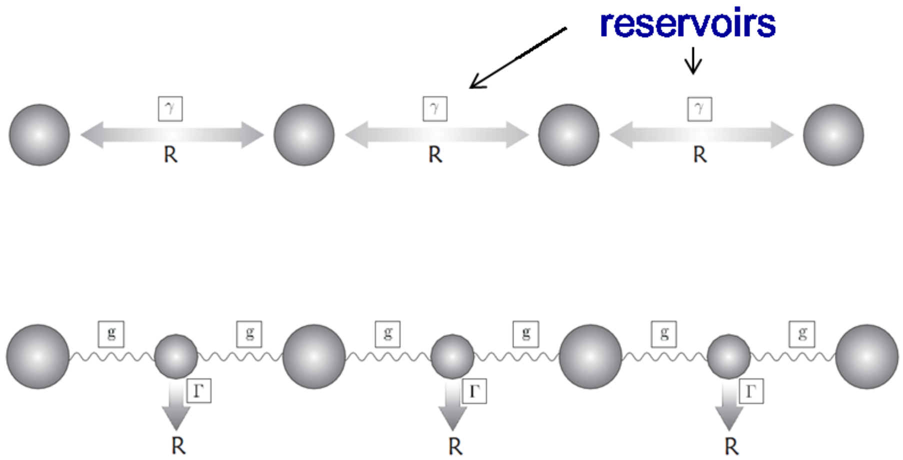
Natalia Korolkova, St Andrews, UK

M. Thornton, *St Andrews, UK*;
D. Mogilevtsev, *Institute of Physics, Bel. Nat. Acad. Sci., Minsk, Belarus*;
S. Mukherjee, R. Thomson, *Photonic Instrumentation Group, Heriot Watt Univ, UK*

Humboldt Kolleg, 29 July – 2 August 2018

Quantum Optics &
Quantum Information

Our "quantum matter":



quantum chain of dissipatively coupled bosonic modes

(or 2D, 3D etc arrangments)

Platform: coherent networks of coupled waveguides

(or trapped ions …)

emulates behaviour of complex systems

Quantumness by dissipation (some examples)

Interaction with a common environment can lead to the creation of an entangled state from an initial separable state

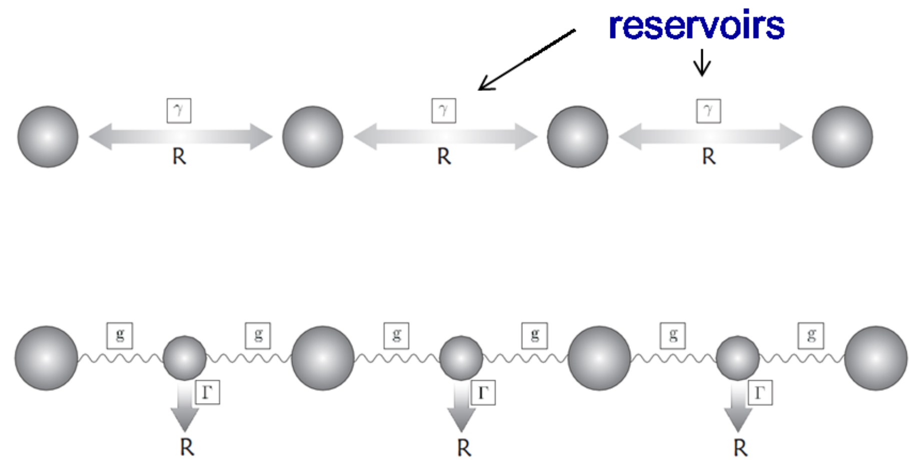
F. Benatti and R. Floreanini, J. Phys. A: Math. Gen. 39, 2689 (2006);
D. Mogilevtsev, T. Tyc, and N. Korolkova, Phys. Rev. A 79, 053832 (2009)

Quantum computation, quantum state engineering, and quantum phase transitions driven by dissipation

F. Verstraete, M. M. Wolf, and J. I. Cirac, Nature Physics 5, 633 (2009)

Dissipatively driven entanglement of two macroscopic atomic ensembles

C. A. Muschik, E. S. Polzik, and J. I. Cirac, Phys. Rev. A 83, 052312 (2011) chain of dissipatively coupled bosonic modes



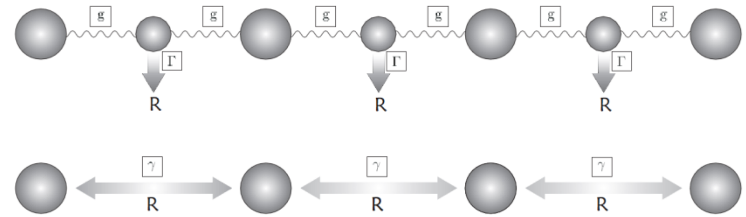
$$\frac{d}{dt}\rho = \sum_{j=1}^{N} \gamma_j \left(2A_j \rho A_j^\dagger - \rho A_j^\dagger A_j - A_j^\dagger A_j \rho \right)$$

$A_j = a_j - a_{j+1}$ - Lindblad operators

$\gamma_j = \gamma$ - relaxation rates into j-reservoir (finite size homogeneous chain)

S. Mukherjee, D. Mogilevtsev, G. Ya. Slepyan, T. H. Doherty, R. R. Thomson, N. Korolkova: Dissipatively Coupled Waveguide Networks for Coherent Diffusive Photonics, Nature Comm. 8, 1909 (2017).

Coupled tight-binding chain of harmonic oscillators



$$\rho(t) = \int d^2\vec{\alpha} P(\vec{\alpha}, \vec{\alpha}^*; t)|\vec{\alpha}\rangle\langle\vec{\alpha}|, \qquad |\vec{\alpha}\rangle = \prod_j |\alpha_j\rangle$$

Lindblad ➔ Fokker-Planck for P-function ➔ Dynamics for coherent amplitudes

$$\boxed{\frac{d}{dt}\alpha_k = -(\gamma_k + \gamma_{k-1})\alpha_k + \gamma_k \alpha_{k+1} + \gamma_{k-1}\alpha_{k-1}}$$

same equation as time-dependent classical random walk in 1D

α_j - complex, no classical probabilities

For dissipatively coupled chain of two-level systems ("fermionic chain") see:
D Mogilevtsev, G Ya Slepyan, E Garusov, Ya Kilin and N Korolkova: Quantum tight-binding chains with dissipative coupling, New J. Phys. 17, 043065 (2015).

Continuous limit – **heat transport Fourier equation** **collective phenomena**

$\langle a_j(t) \rangle$ - 1D heat transport equation for $\langle a(x;t) \rangle$, $x - j$-s mode

$$\frac{d}{dt}\langle a(x;t)\rangle \approx a^2\gamma \, \frac{\partial^2 \langle a(x;t)\rangle}{\partial x^2}$$

$\langle a_j^\dagger(t) a_k(t) \rangle$ - 2D heat transport equation; etc

"heat-like" flow of quantum correlations btw different modes in the chain (can be even entangled); "effective temperature"; heat conductivity - etc

---

Entangled state, e. g. for 1 photon in the chain:

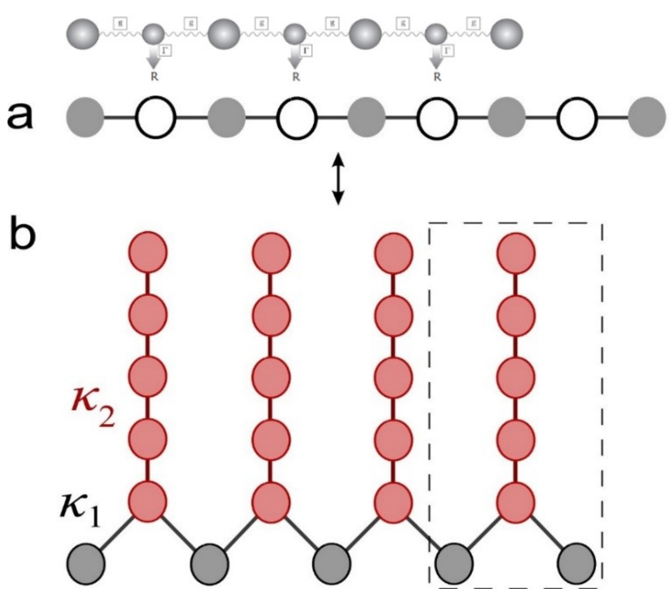
some interesting stationary states

$$|\Phi_{st}\rangle = A_{sum}^\dagger \prod_{\forall j} |0\rangle_j$$

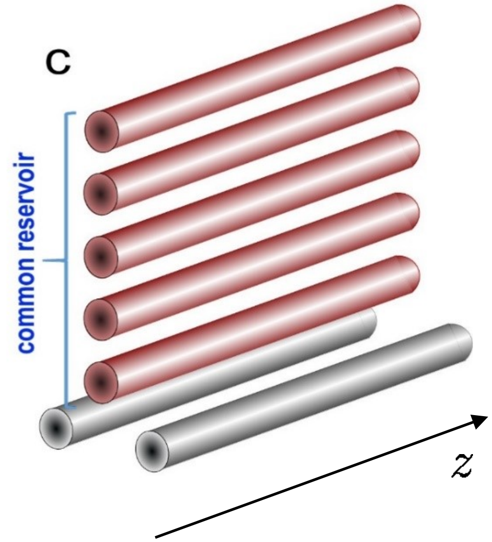
Gibbs state (max. entropy for the given $\sum_{k,l=1}^{N+1} \langle a_k^\dagger a_l \rangle$):

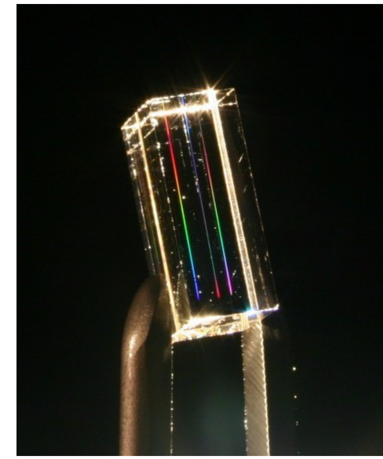
$$\rho_{st} = \exp\{-\beta A_{sum}^\dagger A_{sum}\}/\mathrm{Tr}\{\exp\{-\beta A_{sum}^\dagger A_{sum}\}\}$$

Implementation

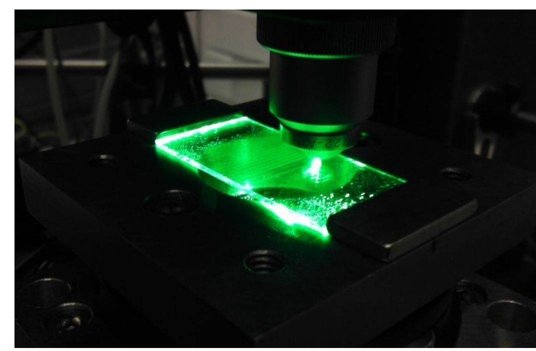


$$\gamma t \Rightarrow z$$



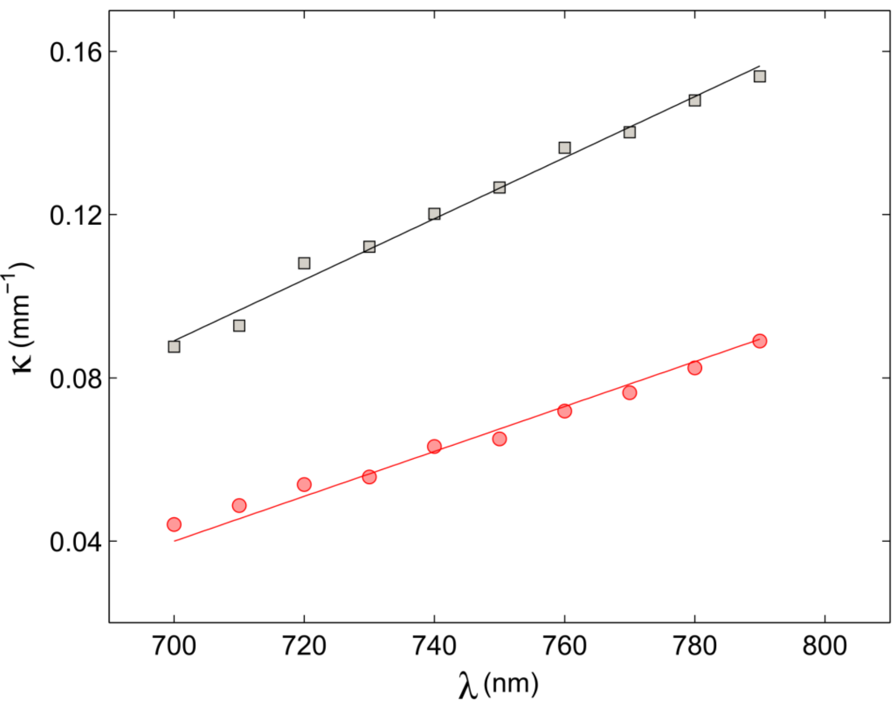


$$\gamma t \leftrightarrow \kappa_1 z \leftrightarrow \kappa_1(\lambda) z_0, \qquad \kappa_1/\kappa_2 \approx 0.5$$

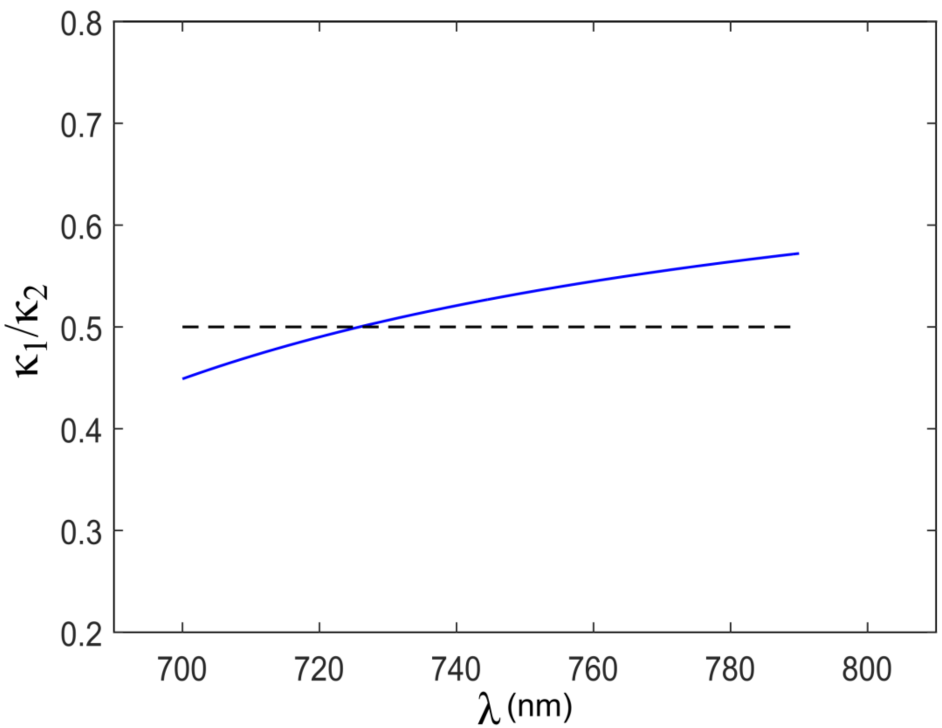


Experiment: Sebabrata Mukherjee and Robert Thomson, Photonic Instrumentation Group, Heriot Watt Univ, UK

$$\gamma t \leftrightarrow \kappa_1 z \leftrightarrow \kappa_1(\lambda) z_0, \qquad \kappa_1/\kappa_2 \approx 0.5$$



$\kappa_1 \rightarrow$ red and $\kappa_2 \rightarrow$ black



κ_1/κ_2 as a function of λ
dashed line: $\frac{\kappa_1}{\kappa_2} = 0.5$ (desired)
blue line: measured;
maximum deviation from 0.5 is $\approx \pm 0.05$

Optical equalizer:

Multi-mode quantum state is symmetrised over all modes

collective symmetrical superposition of all modes: $A_{sum} = \sum_{j=1}^{N+1} a_j / \sqrt{N+1}$

Conserved: average of any function of $A_{sum},\ A_{sum}^{\dagger}$

$$W_1 = \sum_{k=1}^{N+1} \langle a_k(t) \rangle = \sum_{k=1}^{N+1} \langle a_k(0) \rangle$$

collective phenomenon induced by dissipation to common bath

Coherent symmetrisation: output – not a statistical mixture but a pure state

$$\sum_{k=1}^{N}\langle\hat{a}_k(t)\rangle = \sum_{k=1}^{N}\langle\hat{a}_k(0)\rangle$$ - preserved all time

Input coherent state: $|\Psi_{coh}\rangle = \prod_{j=1}^{N} |\alpha_j\rangle_j$

Output: $|\Psi_{purecoh}\rangle = \prod_{j=1}^{N} |\alpha_s\rangle_j = |\Phi_{st}\rangle, \qquad \alpha_s = \frac{1}{N}\sum_{j=1}^{N}\alpha_j$

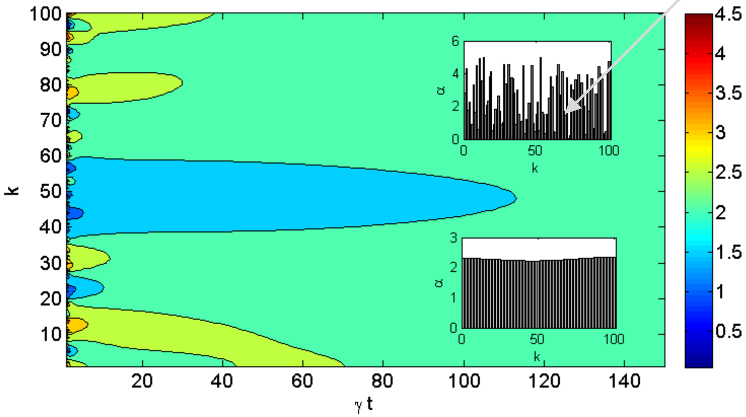
Can eliminate light: for same amplitudes & random phase output tends to zero;

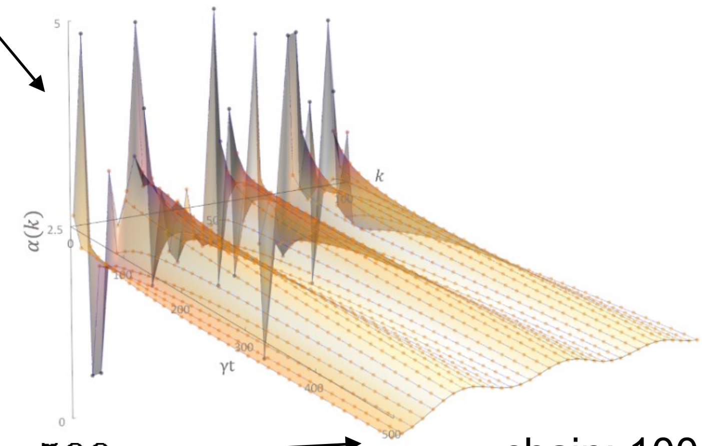
Can supress fluctuations: zero-mean random fluctuations will be smoothed out:

$\alpha_j = \bar{\alpha} + \delta\alpha, \quad \langle\delta\alpha\rangle = 0, \quad N \gg 0$ yields a set of coherent states each with $\bar{\alpha}$

Diffusive equalisation:

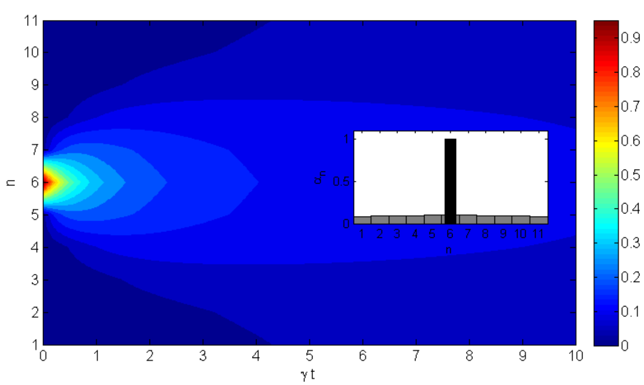
Initial distribution of real coherent amplitudes

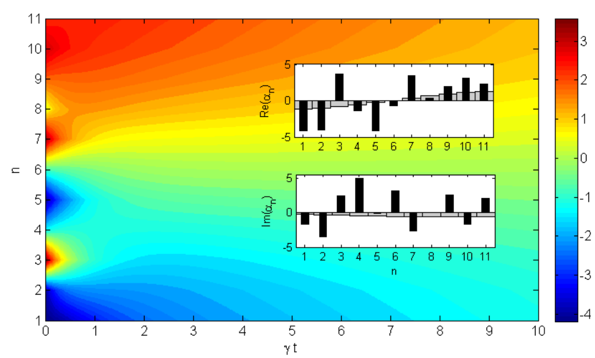




Amplitude distribution at $\gamma t = 500$

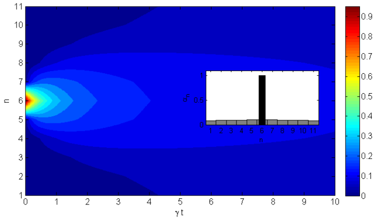
chain: 100 modes



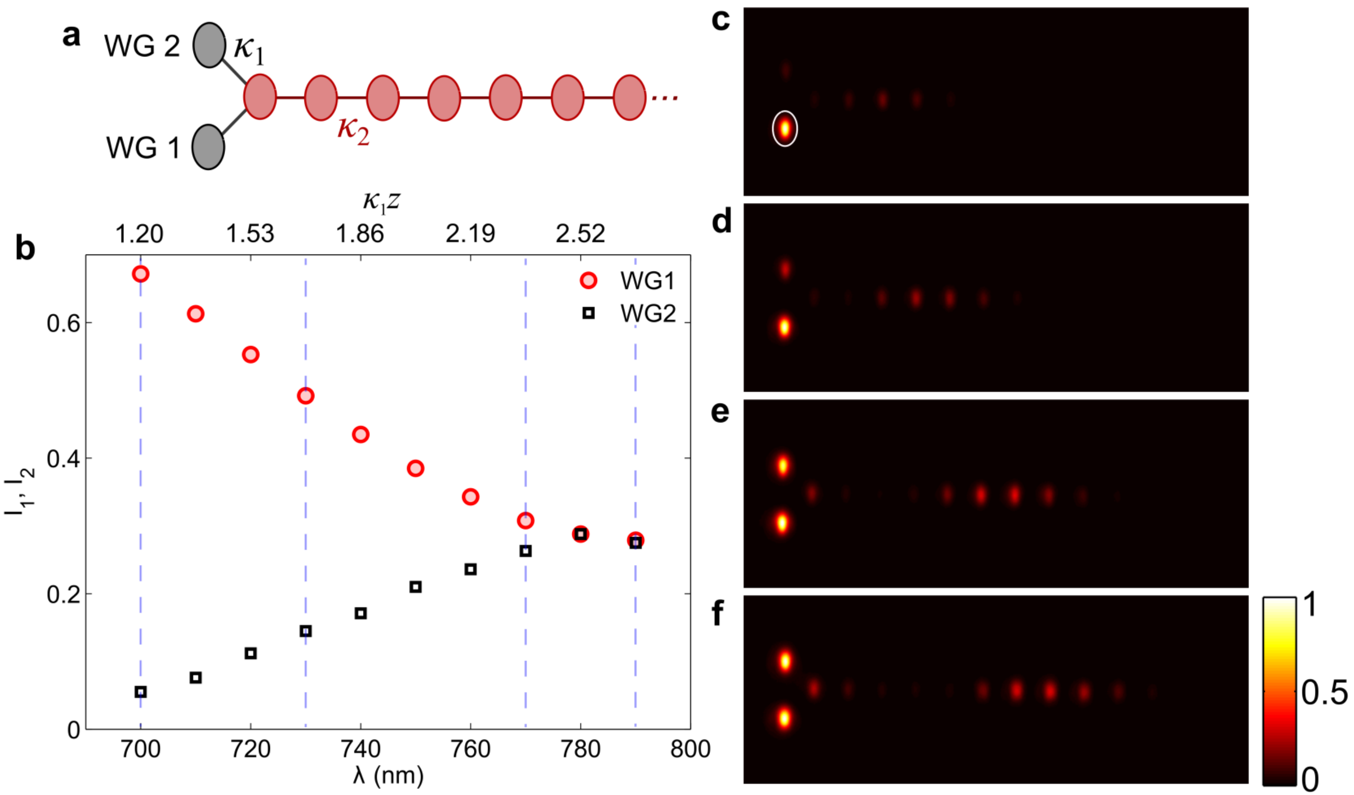


chain: 11 modes

Amplitudes of the coherent states propagating through the dissipatively coupled with equal coupling.

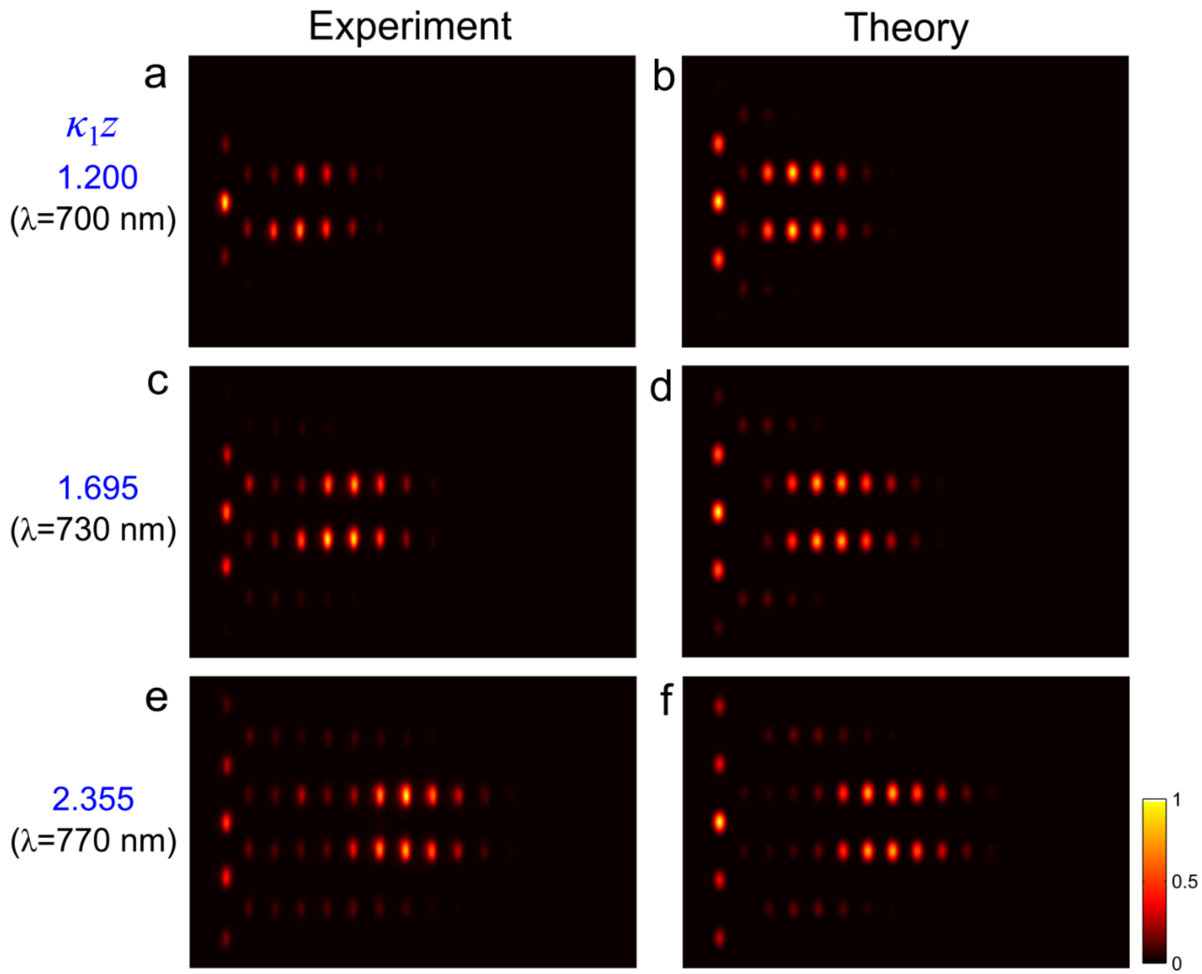


Equalization: experimental results for the simplest element



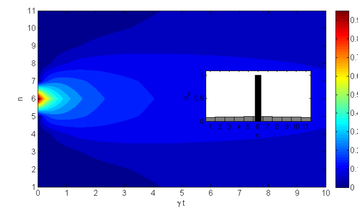
S. Mukherjee, D. Mogilevtsev, G. Ya. Slepyan, T. H. Doherty, R. R. Thomson, N. Korolkova, Nature Comm. 8, 1909 (2017)

Equalization for the chain of 5 waveguides



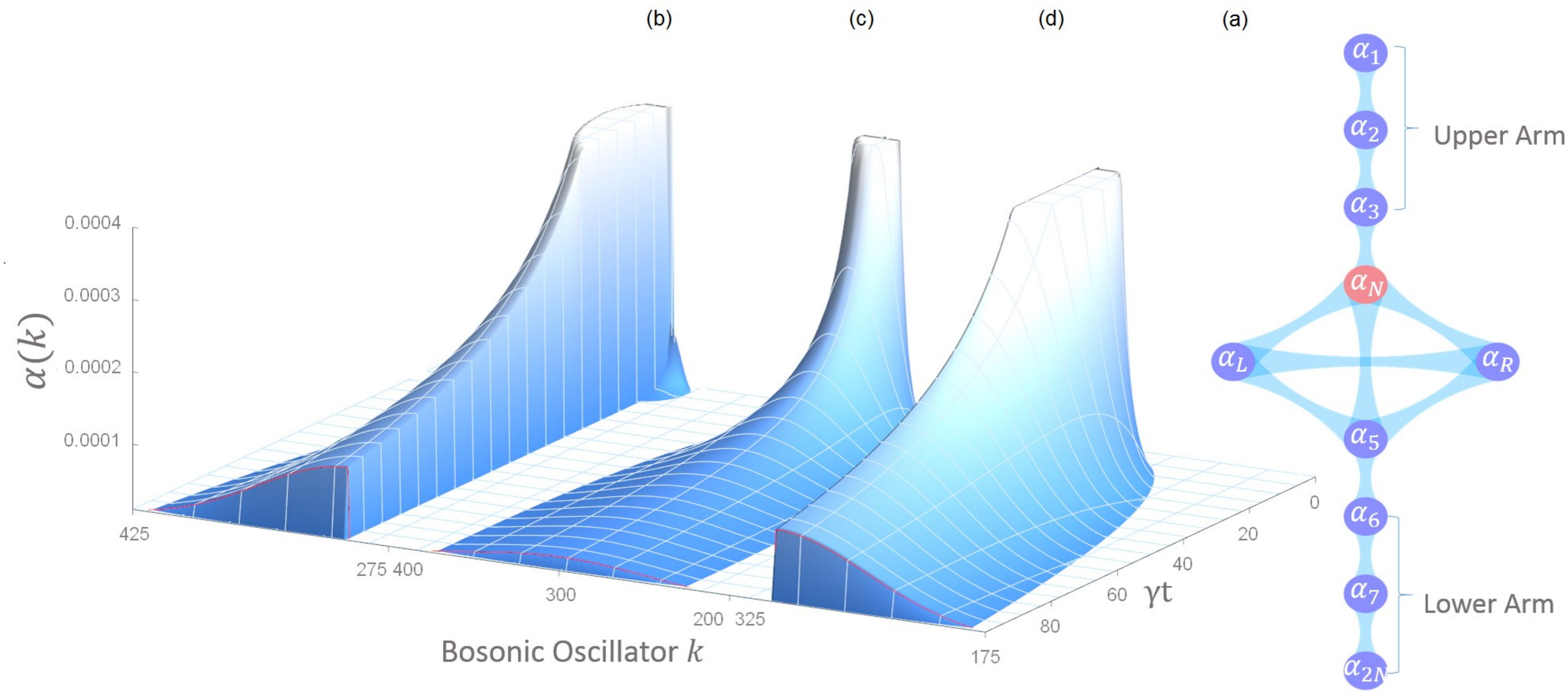
Intensity distributions at the output of the 30-mm-long photonic lattice;

effectively - 5 coupled modes.



S. Mukherjee, D. Mogilevtsev, G. Ya. Slepyan, T. H. Doherty, R. R. Thomson, N. Korolkova, Nature Comm. 8, 1909 (2017)

Diffusive light distribution: $L_{central} = a_N + a_S - a_L - a_R$

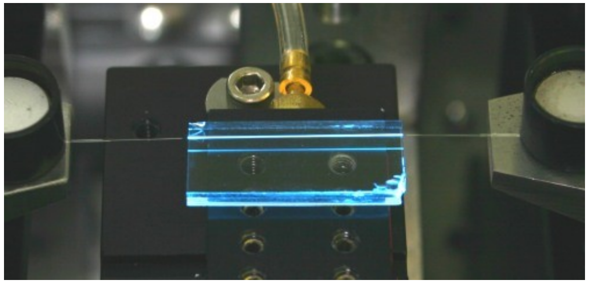


(a) The simplest dissipative distributing structure with two arms. N = 600.

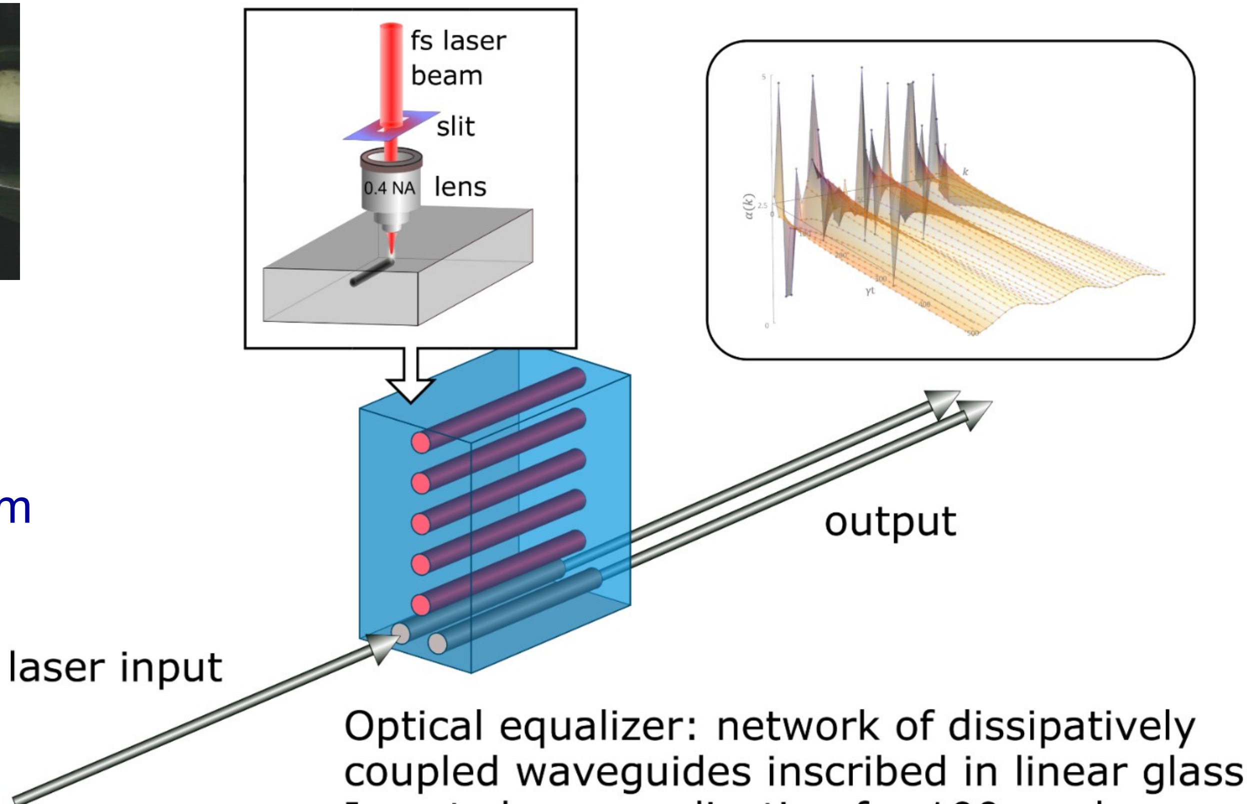
(b) Both control modes R and L are excited equally (or if both control modes are left in the vacuum state). Light is directed into the upper arm only.

(c) When the control mode L is excited initially, the excitation spreads equally into both arms.

(d) When the control modes are excited with opposite phases, light is guided to the lower arm.



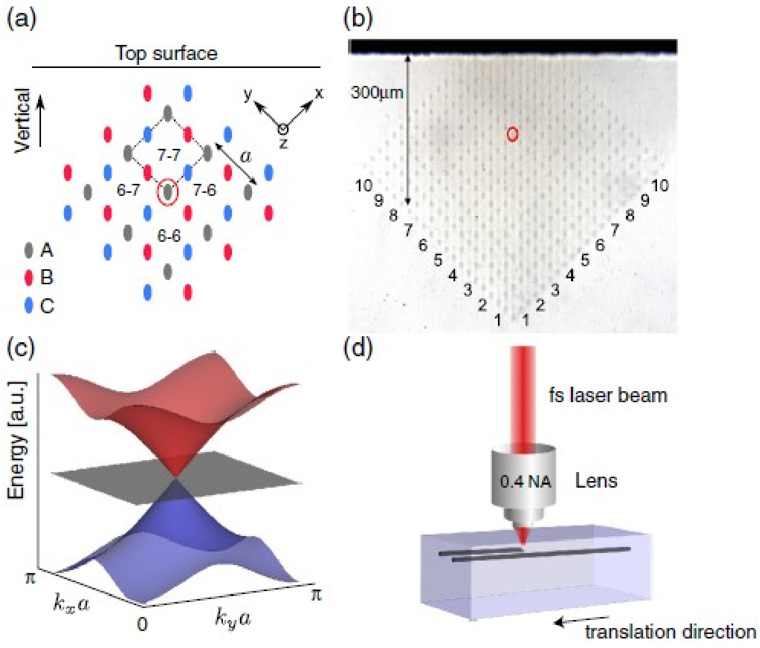
Application: various multi-channel modulation standards in fiber telecomm networks

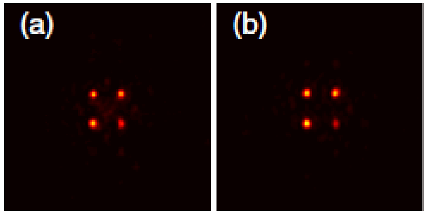


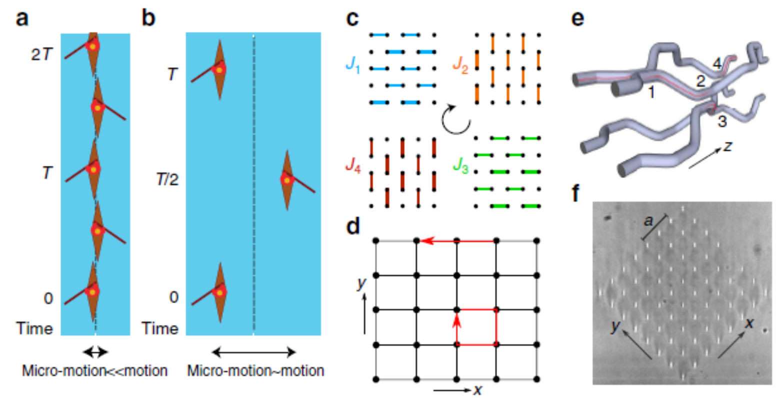
Optical equalizer: network of dissipatively coupled waveguides inscribed in linear glass. Insert shows equlization for 100 modes.

Due to fiber dispersion, different channels may acquire different phases and/or amplitudes after the fiber propagation. These are harmful and lead to loss of data and reduced data rates, hence optical equalization is required.

Beyond the equalisation: diffusive dissipative distribution, optical routing; localization of signal states







S. Mukherjee et al, Observation of a localized flat-band state in a photonic Lieb lattice, Phys. Rev. Lett. 114, 245504 (2015);

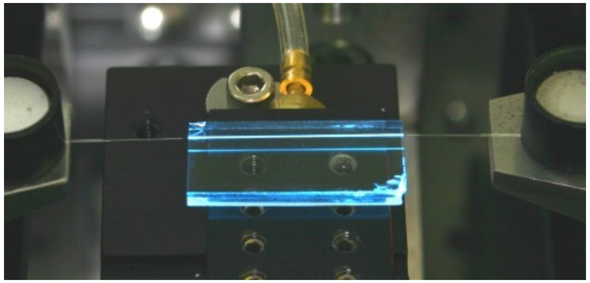
Modulation-assisted tunnelling in laser-fabricated photonic Wannier-Stark ladders, New J. Phys. 17, 115002 (2015);

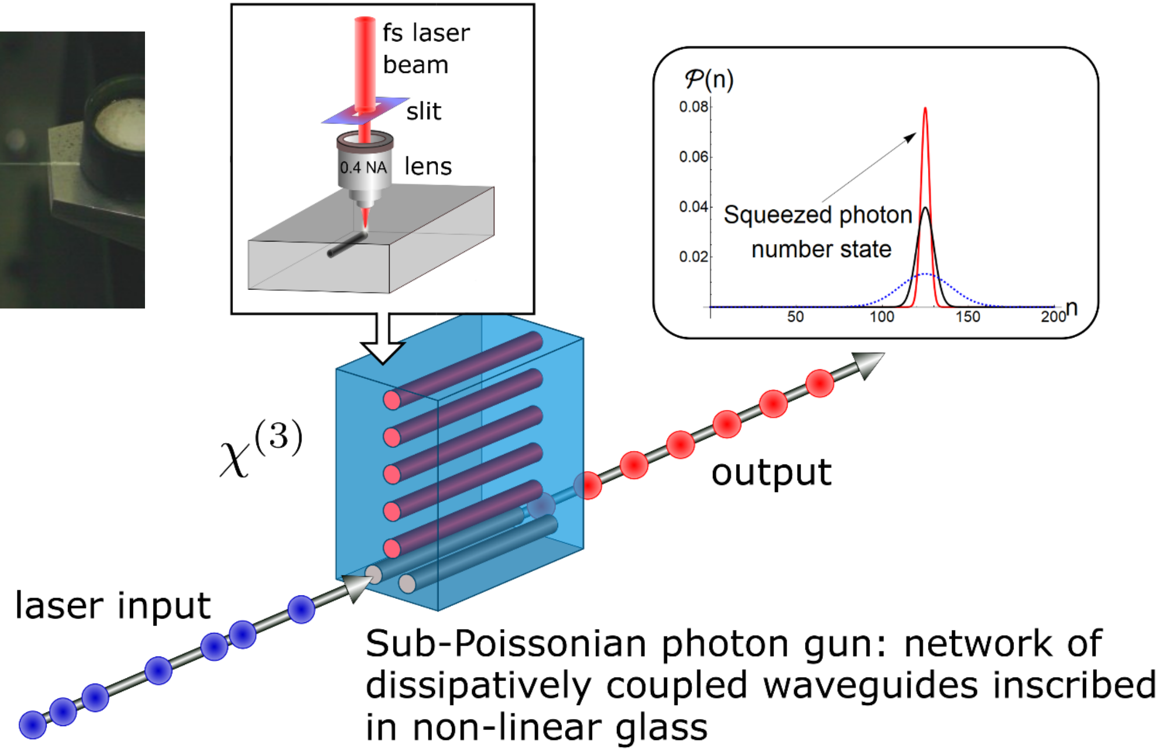
Observation of localized flat-band modes in a quasi-one-dimensional photonic rhombic lattice, Opt. Lett. 40, 5443 (2015)

Experimental observation of anomalous topological edge modes in a slowly driven photonic lattice, Nature Comm. 8, 13918 (2016)

Non-linear dissipatively coupled chain of bosonic modes:

Deterministic generation of few-photon and sub-Poissonian states

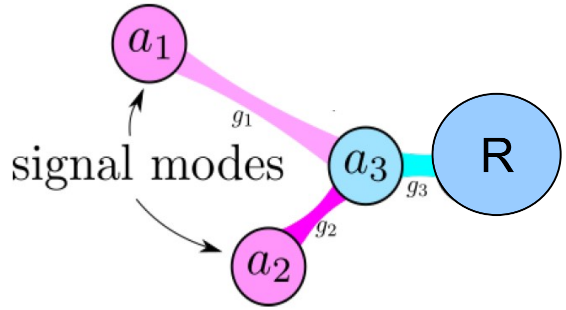




Few-photon (single photon) states on demand, from classical input

D. Mogilevtsev, V. S. Shchesnovich: Single-photon generation by correlated loss in a three-core optical fiber, Optics Lett. 35, 3375 (2010); D. Mogilevtsev, A. Mikhalychev, V. S. Shchesnovich, and N. Korolkova: Nonlinear dissipation can combat linear loss, Phys. Rev. A87, 063847 (2013); M. Thornton, D. Mogilevtsev, N. Korolkova, in preparation.

$|\alpha\rangle$



$\chi^{(3)}$

$g_1 = g_2$

two-photon absorption

$g_1 \neq g_2$

$|0\rangle + \mathrm{e}^{i\varphi}|1\rangle$

$|1\rangle$

phase-state

single-photon

H. Ezaki, E. Hanamura, Y. Yamomoto,
Phys. Rev. Lett. 83, 3558 (1999)

D. Mogilevtsev, V. S. Shchesnovich,
Optics Lett. 35, 3375 (2010)

(atomic gases, exiton-biexiton systems, superconductors)

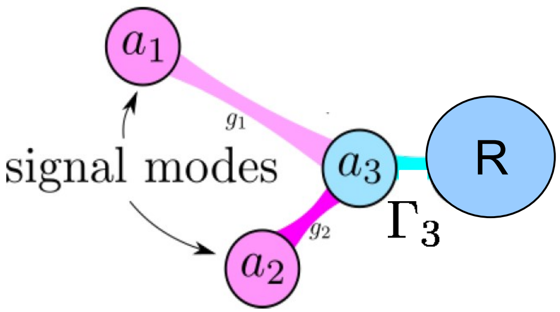
(nonlinear optical waveguides)

from coherent input

$$H=\left[\left(g_1 a_1^\dagger + g_2 a_2^\dagger\right) a_3 + h.c.\right] + \frac{U}{2}\left[\left(a_1^\dagger\right)^2 a_1^2 + \left(a_2^\dagger\right)^2 a_2^2\right]$$

mode 3 can be adiabatically eliminated

$$\frac{\tilde\rho}{dz} = -i[H,\tilde\rho] + (\gamma_{coup/loss}+\Gamma)\mathcal{L}(b_1)\tilde\rho + \Gamma\mathcal{L}(b_2)\tilde\rho$$



for

$$b_1 = (g_1 a_1 + g_2 a_2)/\sqrt{g_1^2+g_2^2}$$

$$b_2 = (g_1 a_1 - g_2 a_2)/\sqrt{g_1^2+g_2^2}$$

forgetting about nonlinearity for a moment: dissipative beamsplitter H

decay of symm collective mode; preservation of antisymm coll mode –

correlated loss, can lead to entanglement generation

Nonlinear interaction between b_1, b_2

The dynamics of the modes is governed by the nonlinear absorption,

which can be tailored by selecting particular absorption channels:

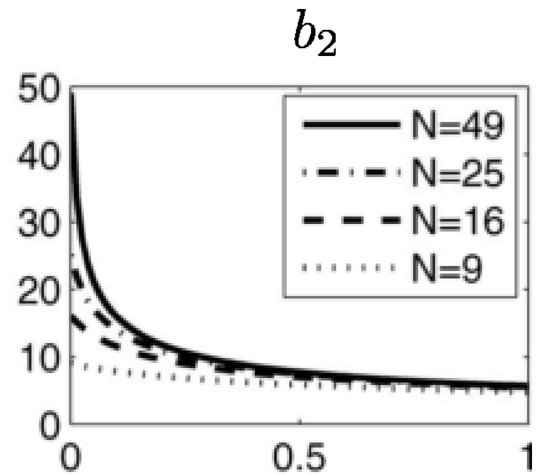
two-photon absorption

three-photon absorption

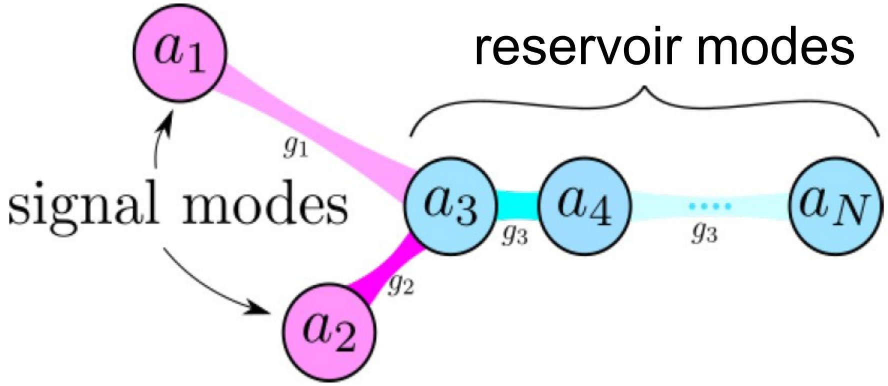
… etc

coupling to common bath,
collective phenomena

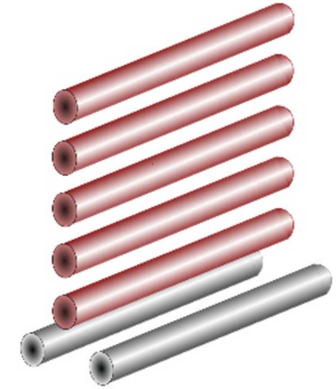
nonlinear absorption



anti-symmetric mode under
two-photon absorption



asymmetric
coupling



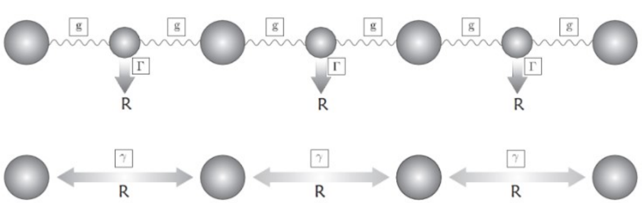
Essential - evolution of symmetric/anti-symmetric coherent superposition of input modes:

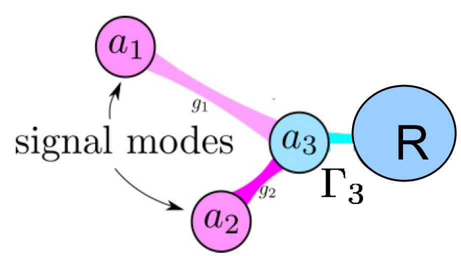
$$b_1 = (g_1 a_1 + g_2 a_2)/\sqrt{g_1^2 + g_2^2}$$

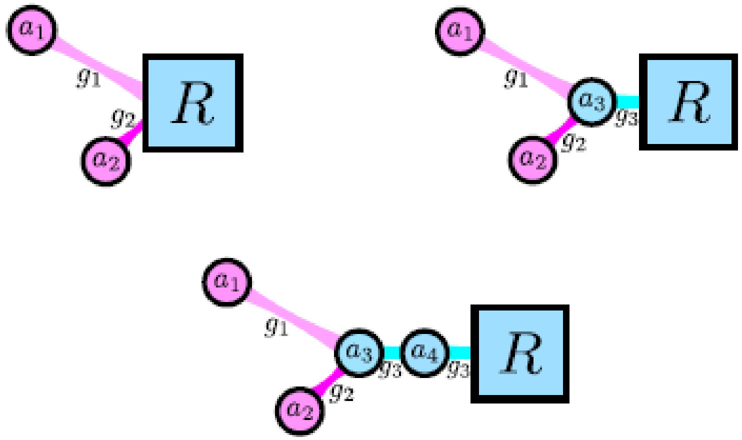
symmetric mode, can be eliminated
and this switches off the single photon loss

$$b_2 = (g_1 a_1 - g_2 a_2)/\sqrt{g_1^2 + g_2^2}$$

anti-symmetric mode, preserved;
this enforces two-photon loss

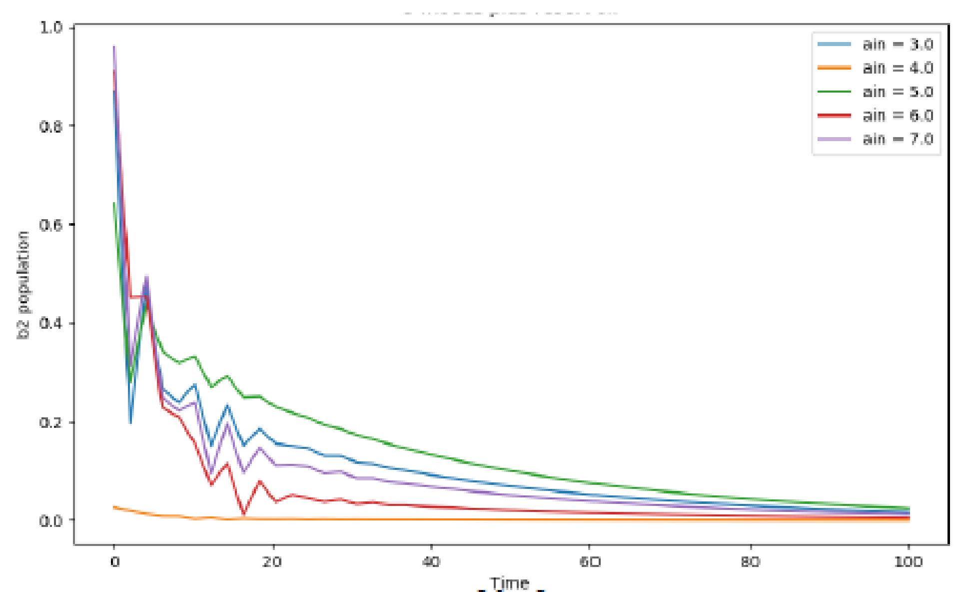






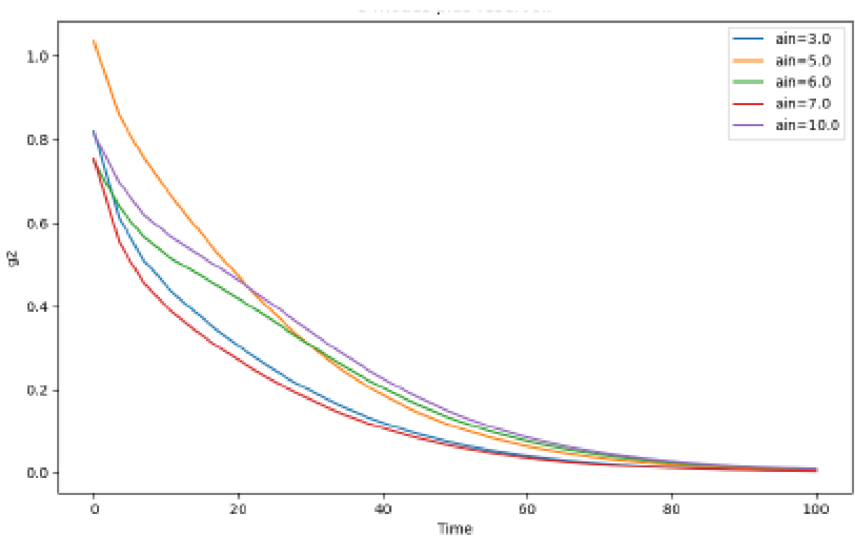
a_1
g_1
g_2
a_2
R
a_1
g_1
a_3
g_3
R
a_2
g_2
a_1
g_1
a_3
a_4
g_3
g_3
R
a_2
g_2

(a)



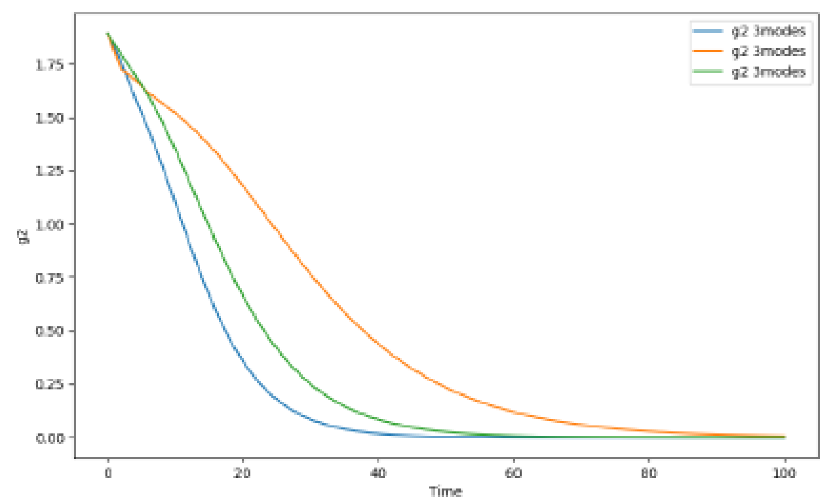
ain = 3.0
ain = 4.0
ain = 5.0
ain = 6.0
ain = 7.0
b2 population
Time

(b)



ain=3.0
ain=5.0
ain=6.0
ain=7.0
ain=10.0
g2
Time

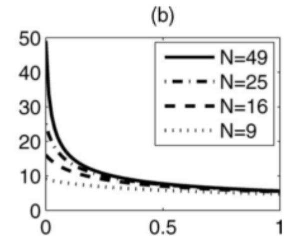
(c)



g2 3modes
g2 3modes
g2 3modes
g2
Time

(d)

asymmetric coupling of two NL waveguides to the third absorptive waveguide



Key: **nonlinear loss and two-photon absorption.**

Engineered loss,

nonlinear loss suppresses linear loss. A set of waveguides loses photons **in pairs**

Two-photon loss leads to rapid narrowing of the photon number distribution

Photon number distribution shifts toward the single-photon state

Single photon state is not affected by two-photon loss, hence stationary for the system

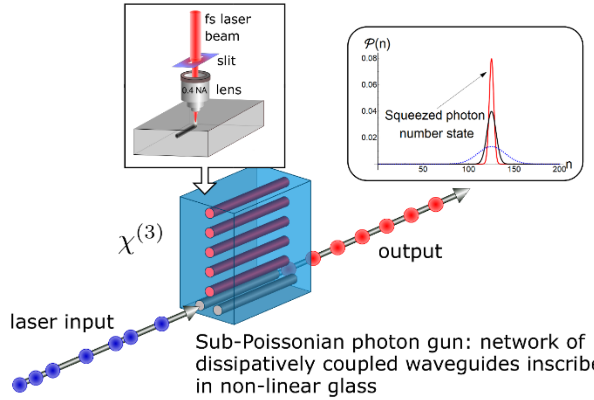
D. Mogilevtsev, V. S. Shchesnovich: Single-photon generation by correlated loss in a three-core optical fiber, Optics Lett. 35, 3375 (2010); D. Mogilevtsev, A. Mikhalychev, V. S. Shchesnovich, and N. Korolkova: Nonlinear dissipation can combat linear loss, Phys. Rev. A87, 063847 (2013); M. Thornton, D. Mogilevtsev, N. Korolkova, in preparation.

Applications – many ….

(where it is important to cut-off multi-photon components)

e.g.: "…a quasi-single-photon source can drastically raise the key rate in the decoy-state QKD"

A. Li, T. Chen, Y. Zhou, and X. Wang, Opt. Lett. 41, 1921 (2016)



Sub-Poissonian photon gun: network of dissipatively coupled waveguides inscribed in non-linear glass





www.st-andrews.ac.uk/~qoi

http://master.basnet.by/lqo

Photonic Instrumentation Group, Heriot Watt Uni, UK


Postdoc positions available, theory & experiment

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SUPA
Scottish Universities Physics Alliance

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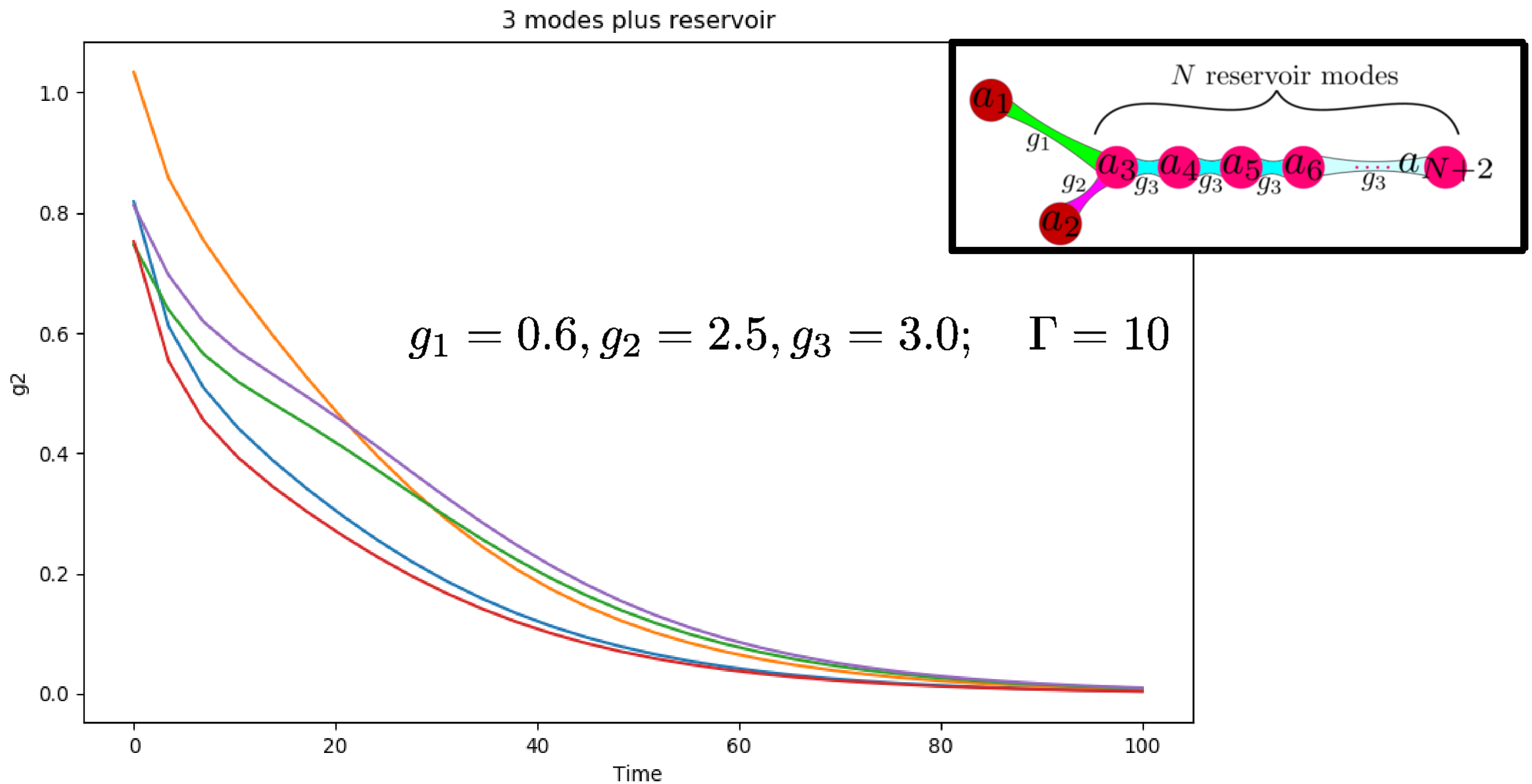
EPSRC Engineering and Physical Sciences Research Council



3 modes plus reservoir
$g_1 = 0.6, g_2 = 2.5, g_3 = 3.0; \quad \Gamma = 10$
N reservoir modes
a_1
a_2
a_3
a_4
a_5
a_6
a_{N+2}
g_1
g_2
g_3
g2
Time
0.0
0.2
0.4
0.6
0.8
1.0
0
20
40
60
80
100