OSCAR[1] Reports–

an SFB/TR 185 quarterly magazine (4/2019)

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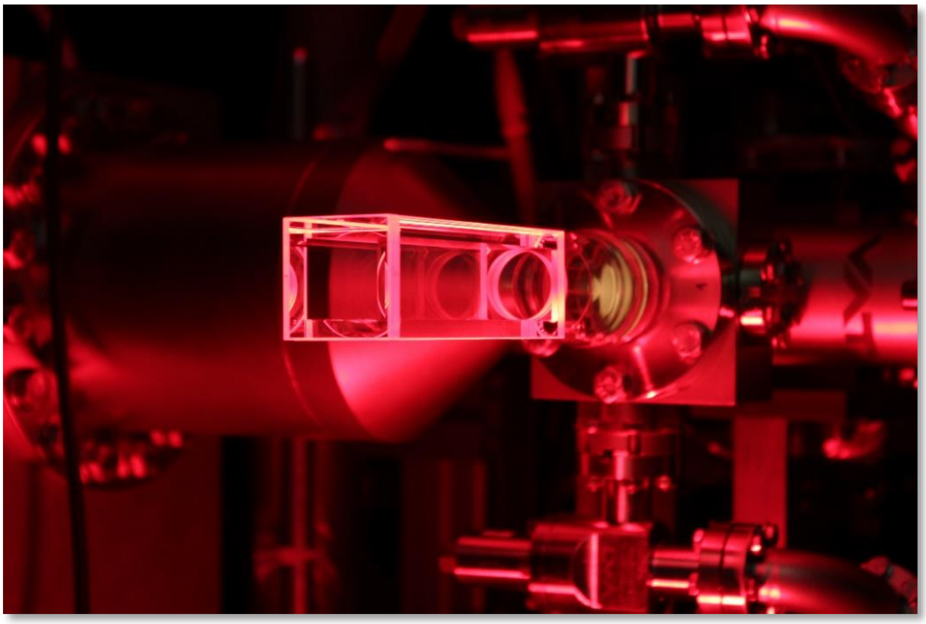

[1] stands for **O**pen **S**ystem **C**ontrol of **A**tomic and Photonic Matte**R;** funded by the Deutsche Forschungsgemeinschaft since July 01, 2016

Correlated photon-pair generation in a liquid-filled microcavity (Area A)

Combining resonators with liquid nonlinear media opens new ways to control properties of entangled photons

F. Rönchen, T. Langerfeld, M. Köhl

New J. Phys. **21**, 123037 (2019)

Correlated or quantum entangled photon pairs have been a working horse for our understanding of quantum mechanics and form a basis for emerging quantum technologies. Therefore, the controlled and efficient preparation of such states is of central importance. Standard methods used are spontaneous parametric down-conversion or four-wave mixing processes, which usually employ the optical nonlinearities of solids to provide correlated photon pairs within a spectral bandwidth of several THz. The use of high-quality optical resonators allows both to increase the intra-cavity field strength and to control the emission bandwidth of the entangled photon pairs. The group of M. Köhl has followed an approach to employ the nonlinearity of a fluid-filled optical resonator for realizing spontaneous four-wave mixing (SFWM) producing entangled photon pairs with a tunable bandwidth and markedly increased rate.

In a resonator, SFWM converts two photons of the pump field at an angular frequency ω_0 into photon pairs at frequencies $\omega_{n,\pm} = \omega_0 \pm n \cdot \omega_{FSR}$, where $\omega_{FSR} = \frac{\pi c}{L}$ is the free spectral range of the resonator of length L, c is the speed of light, and n is an integer counting the order of the process. Experimentally, the group has constructed a microscopic optical resonator comprising the micromachined end facet of an optical fiber and a conventional planar mirror. It features a resonator length of only $L = 38$ µm, resulting in a free-spectral range of the empty cavity of 3.9 THz. The cavity finesse amounts to $F = 12500$. The nonlinear liquid filling the resonator is a synthetic silicone oil with refractive index $n = 1.556$, showing very high optical quality, specifically an absorption coefficient as low as $5\ \mathrm{m}^{-1}$. This setup combines the advantages of resonator optics with liquid nonlinear media: The cavity allows control over the emission bandwidth of the entangled photon pairs, ideally for the whole range where the mirrors are highly reflective. The liquid filling allows using materials with relatively large nonlinear refractive indices. It furthermore reduces the number of interfaces between different refractive indices in the resonator, which might reduce the cavity's performance. Finally, the liquid filling reduces thermal effects because heat convection in a liquid dissipates the inserted heat by absorption much faster than heat conduction, which dominates in solids. These properties lead to a moderate temperature increase of only 0.2 K, even for intra-cavity powers approaching the Watt regime.

Spectrally dispersing the cavity output by a grating spectrometer and correlating the signals of two single-photon counting modules (one for the $+n$th and the $-n$th order) allows deducing two-photon correlation signals as shown in Fig. 1. It demonstrates the nonclassical origin of the photon correlation. Importantly, not only the first order $n = 1$, separating the signal-photon frequency from the pump frequency by one free-spectral range, but up to third order has been realized.

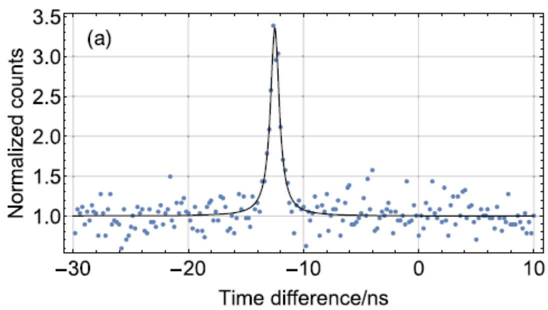

Fig. 1: Two-photon coincidence signal for $n = 2$ at intracavity power of 0.58 W.

The technological step presented is an important one to employ resonators as a fundamental building block to assemble optical Hubbard-type systems. Here, dissipation is crucial for understanding and controlling the steady-state properties and phase diagram of open quantum systems.

Thermally condensing photons into a coherently split state of light (Area B)

Photonic wave packets can coherently populate a double-well potential in microcavities

C. Kurtscheid, D. Dung, E. Busley, F. Vewinger, A. Rosch, and M. Weitz

Science **366**, 894 (2019)

Macroscopic, coherent quantum states, such as atomic Bose-Einstein condensates (BEC) in dilute atomic vapor, superfluid Helium, or superconducting states, are usually established by cooling the system below a critical temperature. The underlying process requires the dissipation of excess energy and is thus irreversible. By contrast, coherent states of light are prepared and manipulated by unitary, i.e., reversible operations such as beam splitters. The group of M. Weitz has used their experience in controlling photonic BEC to show the condensation of photonic wave packets in a double-well potential and to demonstrate the coherence of the emerging state.

A quasi-two-dimensional (2D) photonic BEC can be realized in an external pumped, dye-filled microcavity having a finesse close to 100,000. Laser-based local heating on one of the mirror substrates imprints a local change of the reflective surface, leading to an effective double-well potential for photons when operated in the cavity, see Fig. 2. This potential is overlapped with an overall harmonic confining trap necessary for BEC creation. The pump photons are absorbed and reemitted by the dye molecules, where the resonator imposes a cutoff of wavelengths supported. The longitudinal population of the resonator is unchanged due to its large free spectral range, and the remaining two-dimensional photon gas in the transverse direction can thus thermalize via interaction with the dye.

Once the BEC regime has been reached by exceeding the critical photon number through increased pumping, the cavity emission shows a bright double peak emission representing the in-situ image of the split condensate. Overlapping the emission profiles results in high-contrast interference fringes demonstrating the coherence of the wave packets in the split BEC (see Fig. 3). This interference is stable, which can be understood from a time-scale separation between the tunneling time in the well of ≈ 17 ps establishing coherence and being much faster than the typical time of absorption and emission cycles of the dye of ≈ 100 ps.

The work paves the way for investigations of open-quantum-system properties in more intricate potentials or including nonlinear interactions, where quantum states become accessible that are not accessible in conventional atomic physics realizations so far.

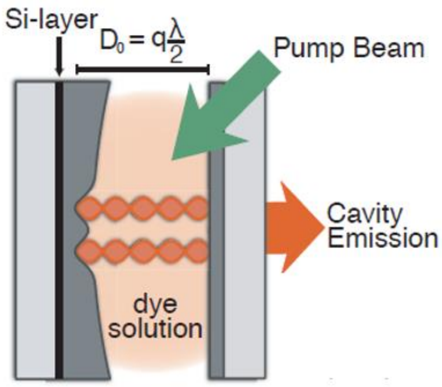

Fig. 2: Experimental setup. A dye-filled cavity confines a 2D photon gas, thermalizing with a dye solution. A microstructured mirror surface creates a double-well potential for the photon gas. The spatial light distribution of the cavity emission is recorded by a camera.

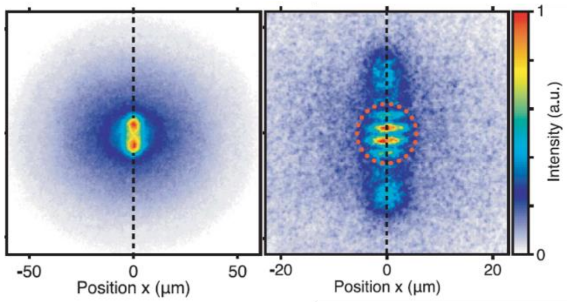

Fig. 3: Images of cavity emission in the BEC regime. Left: In-situ image of the split condensate. Right: Interference fringes resulting from overlapping the two peaks of the cavity emission.

Observation of topological transport quantization by dissipation in fast Thouless pumps (Area A&C)

Nonhermitian Floquet-driving opens new routes for realizing quantized Thouless pumping

Z. Fedorova (Cherpakova), H. Qiu, S. Linden, and J. Kroha

ArXiv:1911.03770 (2019)

Quantized dynamic arises not only from discrete energy spectra but also from a nontrivial topology of the Hamiltonian parameter space. A standard way to implement quantized transport is to slowly vary system parameters periodically along a closed loop in such a parameter space. In a theory-experiment collaboration, the teams of S. Linden and J. Kroha have proposed and demonstrated that using non-Hermitian Floquet drive realized as time-periodic dissipation, fast Thouless pumping can be achieved.

The model considered is a modified time-periodic Rice-Mele (RM) model, which originally describes a chain of coupled dimers with periodically changing system parameters. This model is extended by adding time-periodic dissipation. An analysis using Floquet theory for non-Hermitian, time-periodic systems shows that the mean displacement of a single-particle wave packet per cycle is quantized. Importantly, this quantized transport prevails even when the driving is fast, i.e., far from adiabaticity. Experimentally, surface plasmon-polaritons in waveguides are ideally suited to realize such models. The propagation realizes a single-particle Schrödinger equation, where time is replaced by propagation length. Here, periodically modulated tunneling strength and dissipative loss can be implemented by modulating the waveguides' mutual distance and the individual waveguide's cross-section, respectively, see Fig. 4

The plasmon polariton wave package is detected by recording the radiation leaking from the waveguide and either imaged directly to obtain a real-space image or imaging the Fourier plane of the radiation pattern onto a camera.

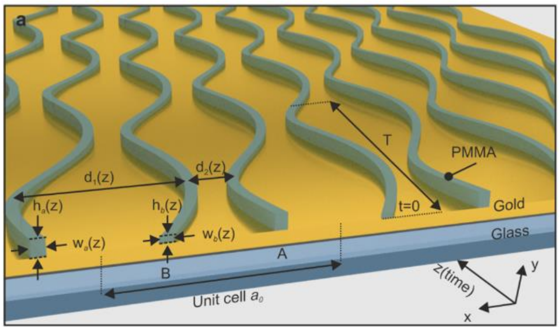

Fig. 4: Sketch of plasmon-polariton waveguides on a gold substrate. The waveguides have been fabricated with periodic mutual distance and periodically varying cross section. Light is coupled into one of the ports, and the excitation propagation is studied along z using radiation leakage.

The real-space images (see Fig. 5) show that, while dissipation-free transport features dispersion due to waveguide-coupling and interference, the dissipative case exhibits directional transport. Intuitively, this can be understood as the engineered dissipation selectively suppressing modes which would lead to a transport in the other direction.

The work constitutes an example for open system control, using dissipation to steer a quantum system in a desired way, and it offers a theoretical and experimental platform to study this new approach of dissipative Floquet engineering in so far unexplored systems.

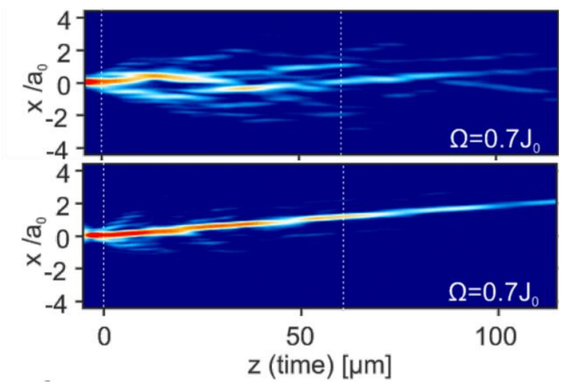

Fig. 5: Measured plasmon propagation in waveguides without loss is dispersive (top). Waveguides with periodic loss included show directional transport (bottom).