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Potential Applications of Semiconductor Nanolasers in Particle Detection and Speckle-Free Illumination

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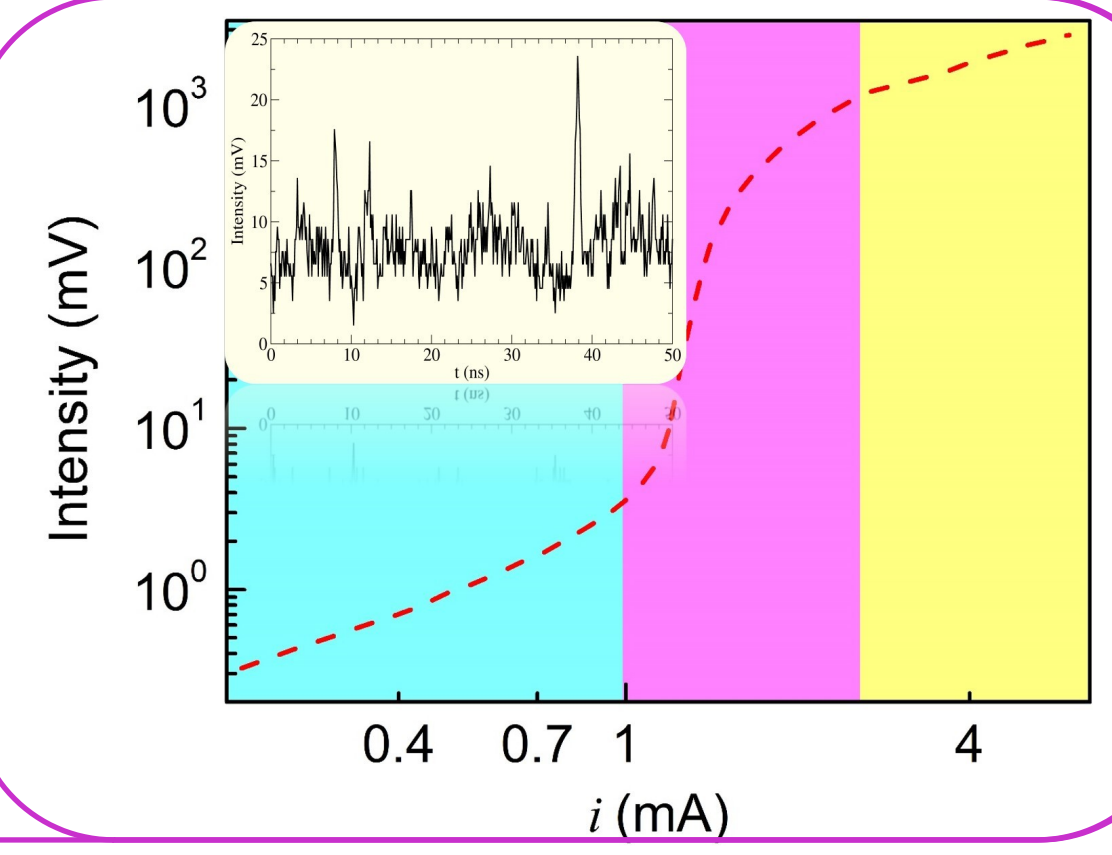
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Background Photon bursts experimentally observed [1] in microlasers (orange background region).

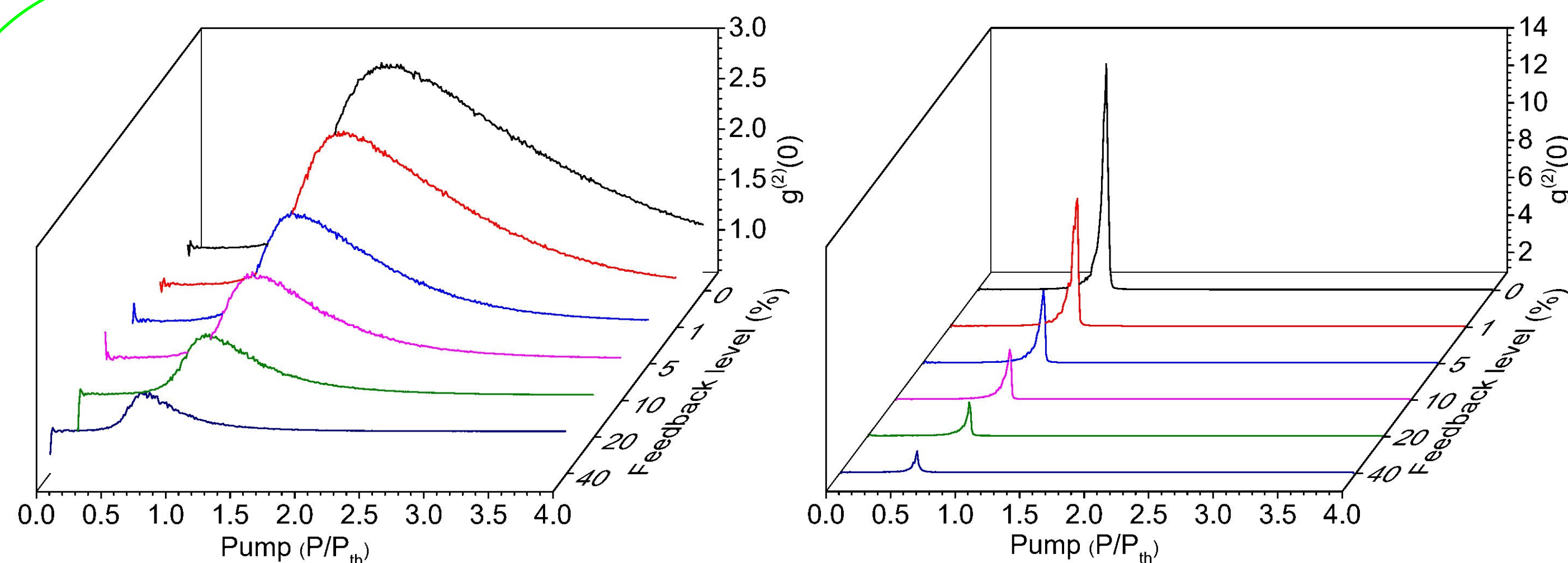
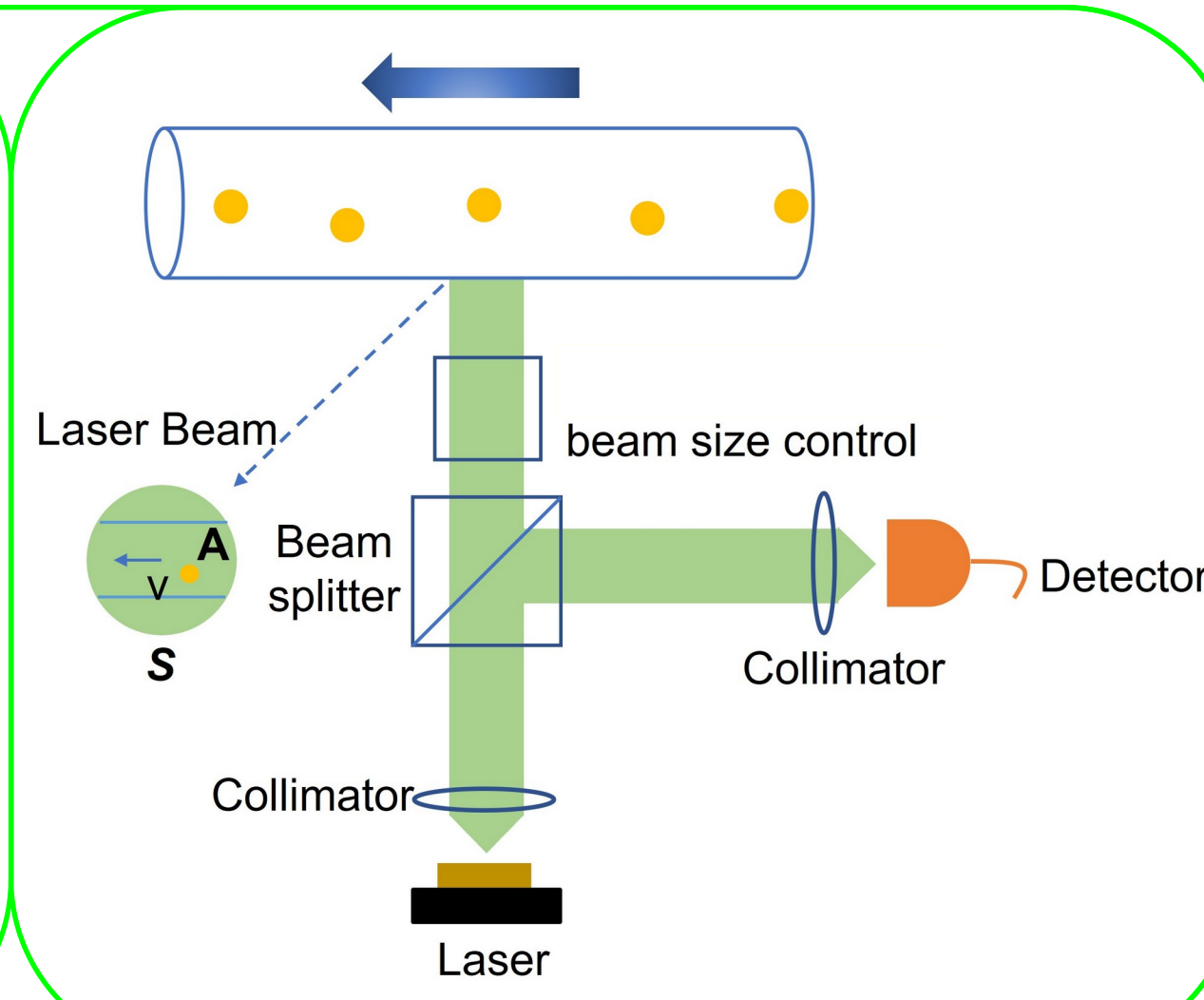
- Predictions of photon bursts in stochastic simulations [2] in micro- (e.g., $\beta = 10^{-4}$) and nanolasers (e.g., $\beta = 10^{-1}$).
 β : fraction of spontaneous emission coupled into the lasing mode.
- Result of the combination of large carrier fluctuations and poor excitation transfer from energy reservoir (carriers) to the field. Newly discovered regime offers opportunities for exploiting the unusual dynamics in different fields of application.
- Two applications are explored in which feedback modifies the spontaneous photon-burst regime.



Particle Sensing

Implementation:

Scattering particles flow at variable speed – ($0.01 < v < 10$)m/s
 Medium: air or liquid
 Backscattering of incident beam introduces feedback into the laser
 The photon autocorrelation function is used to characterize the changes introduced by feedback (related to particle size and nature)



The zero-delay second order photon correlation function ($g^{(2)}(0)$) characterizes the statistics of the emitted photons.

Microlaser (right): superthermal statistics (0% feedback, black) signals strong photon bursts – progressively reduced to subthermal levels – in a very narrow range of pump values close to threshold.

Nanolasers (left): weaker superthermal statistics persisting over a very broad pump range.

Emission is affected by feedback in both cases, to different extents, allowing for separate quantification ranges of particles and speed [3].

Speckle-Free Illumination

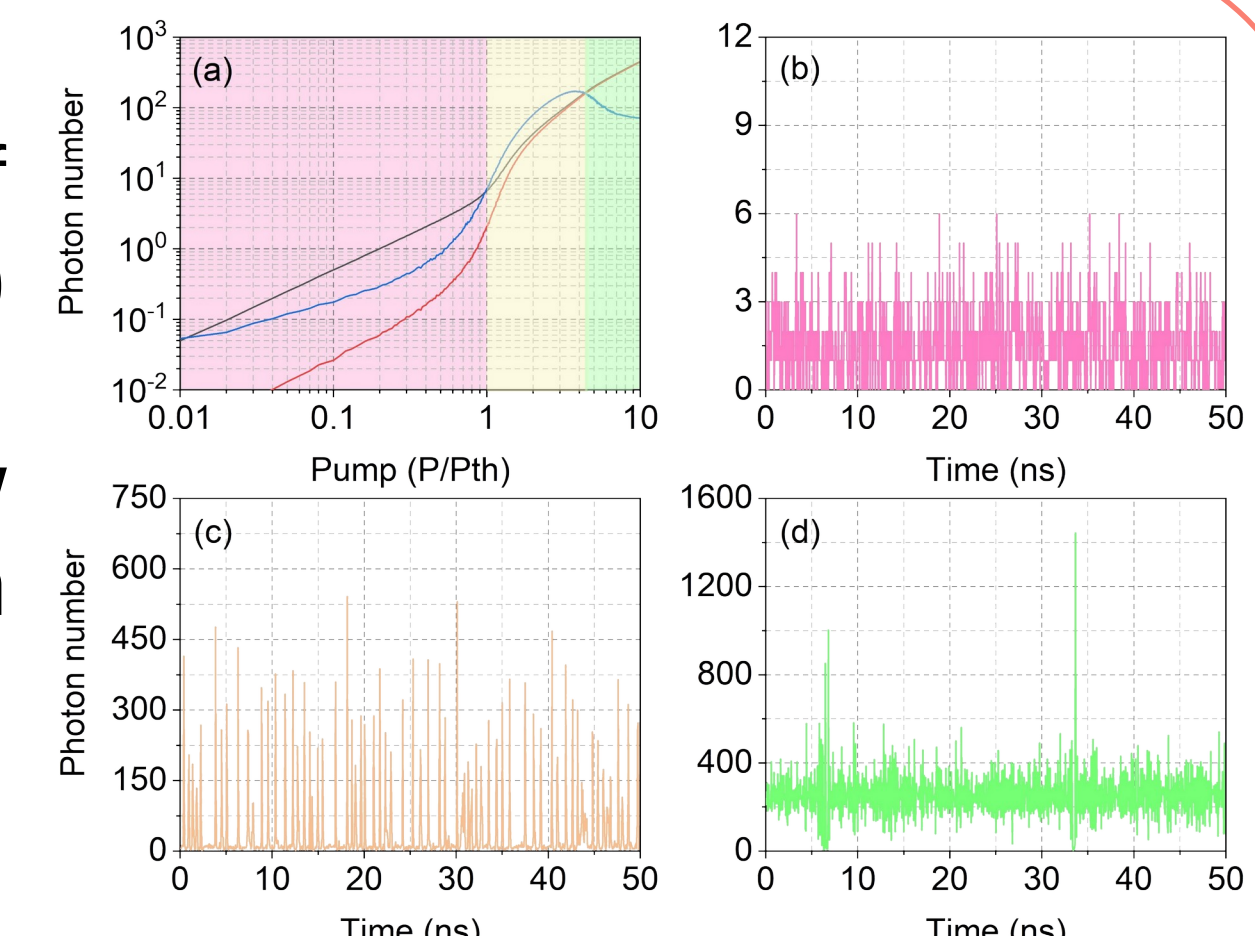
Background:

Nanolaser response curve (black) consists of spontaneous (blue) and stimulated (red) events.

Sharp photon bursts appear in the yellow region and can be exploited by adding an amount of external feedback ($\tau_{fb} = 4$ ns).

Predictions based on stochastic simulations

[2] require a careful analysis of the signal to avoid spurious interburst coherence [4]. A longer (fibered) feedback arm enables expanded sequences of independent pulses.



Independent pulse trains

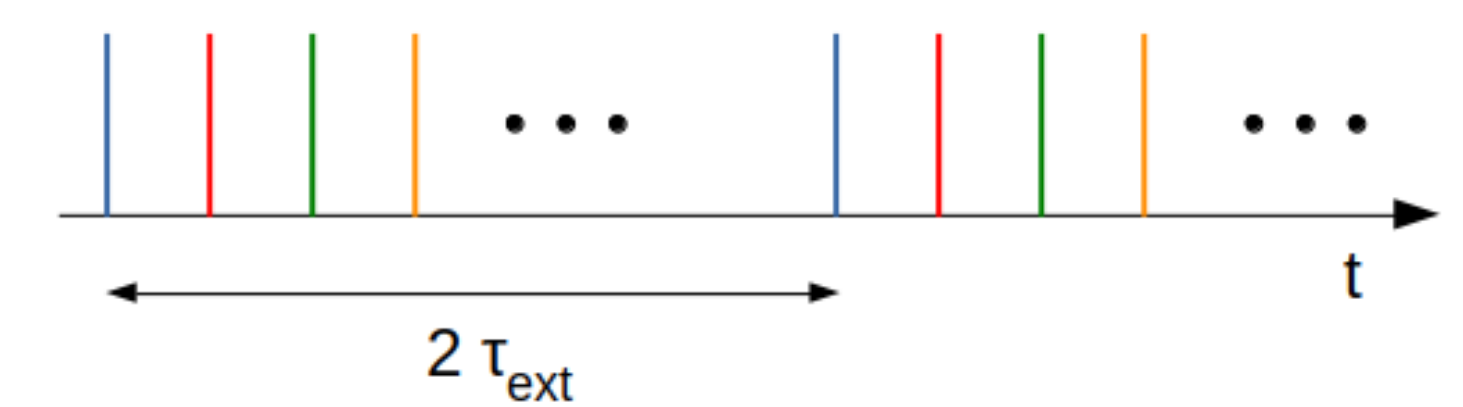
• Partial coherence between pulses may emerge from photon reinjection by the feedback arm. The fraction of incoherent pulses [4] is analysed in the table.

• Increasing the feedback level leads to a larger degree of mutual coherence (second line).

• However, independence between neighbouring pulses (initiated by spontaneous seeds) allows for the generation of pulse trains which remain optically decorrelated even in the presence of partial correlation over a roundtrip of the external cavity.

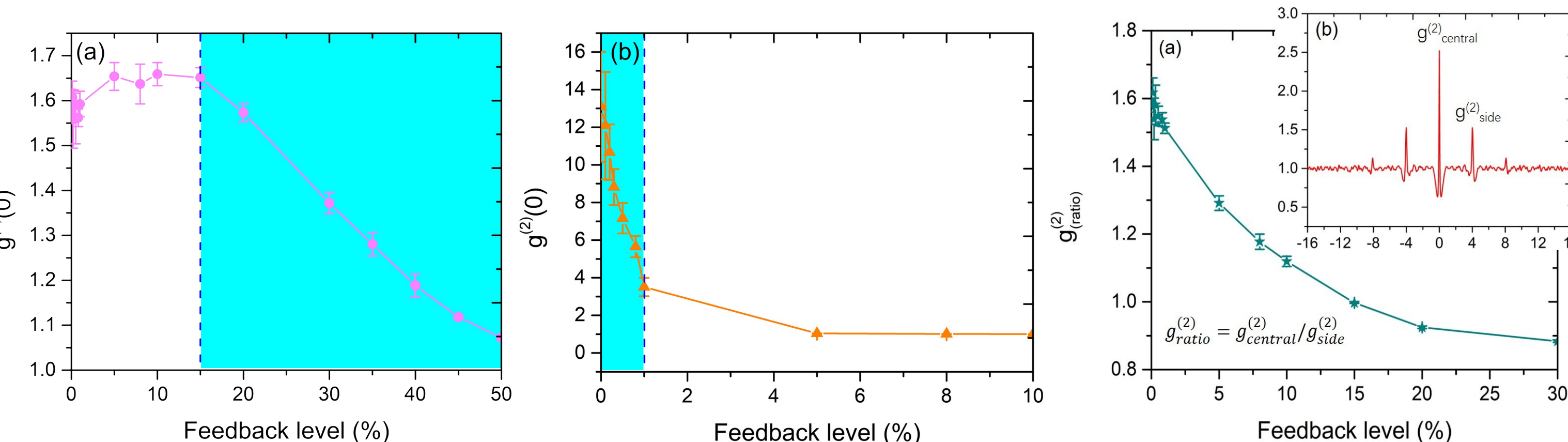
• Increasing the feedback length (an easy task with an optical fiber) enables the generation of a larger number of pulse trains, which lower the mutual coherence.

Feedback (Spont./All) Pulses	0.5%	1%	5%	10%
Indep. Pulse Trains	0.76	0.67	0.35	0.24
	18.2	19.3	21.5	22.9



Feedback coverage: With suitable sensitivity, all feedback values can be measured (covering diverse particle sizes, scattering coefficients and setup choices) from $< 1\%$ (microlaser) to $\sim 50\%$ (nanolaser).

Intermediate feedback (1% ... 15%) is quantified with the time-delayed autocorrelation ($g^{(2)}(\tau)$) [3].

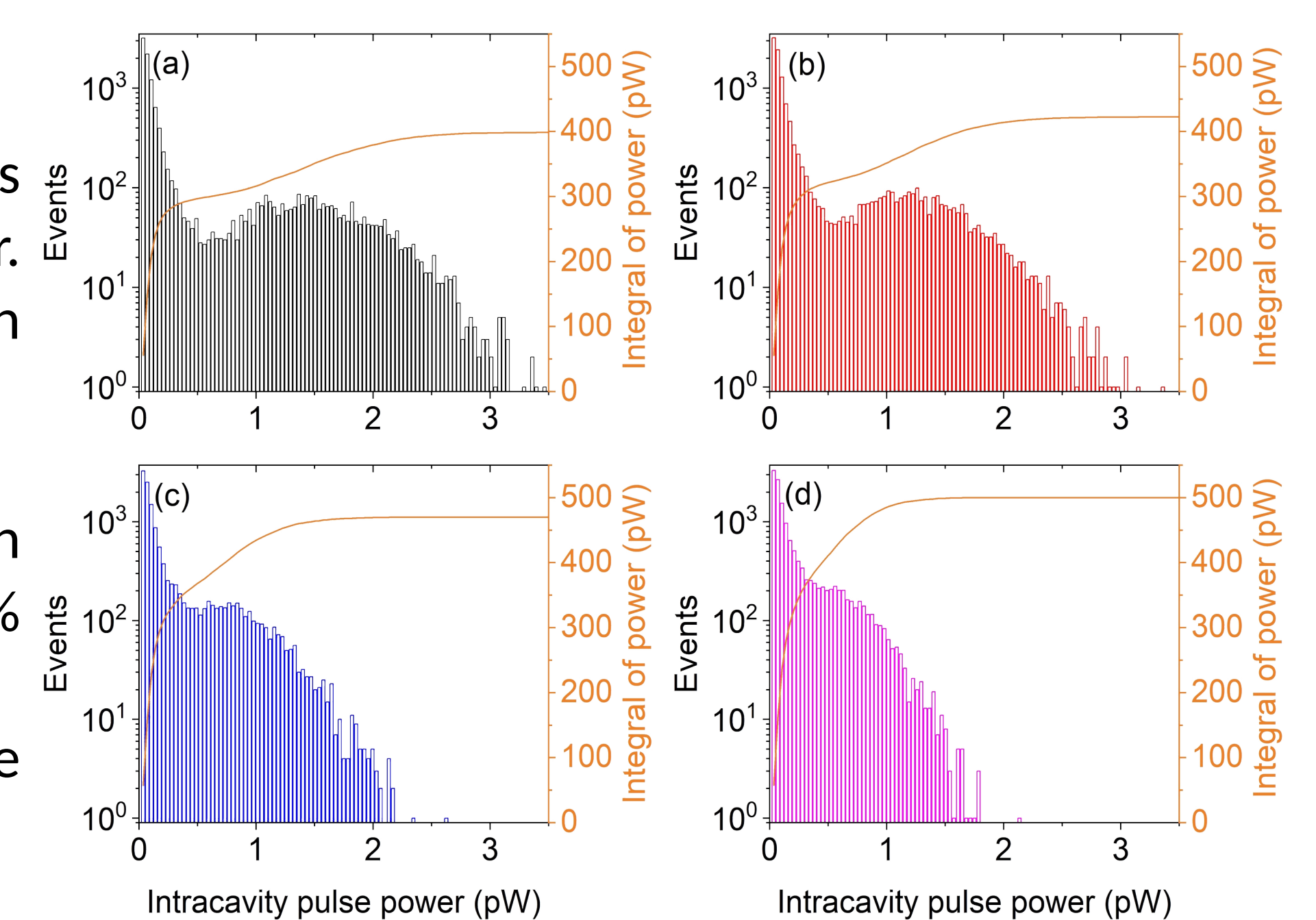


Pulse power distribution

• The feedback fraction controls the distribution of pulse power.
 • More homogenous distribution with increasing feedback.

• Integral power (solid line): 90% carried by pulses with power below ~ 0.7 pW at 10% feedback

• At 0.5% feedback for the same fraction we find pulses up to ~ 1.7 pW.



Conclusions:

The peculiar emission in photon bursts offers so far unknown avenues for new kinds of applications based on the intrinsic properties of this low coherence regime.

References

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- [2] G.P. Puccioni and G.L. Lippi, *Stochastic Simulator for modeling the transition to lasing*, Opt. Express **23**, 2369-2374 (2015).
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- [4] T. Wang et al., *Nanolasers with Feedback as Low-Coherence Illumination Sources for Speckle-Free Imaging: A Numerical Analysis of the Superthermal Emission Regime*, Nanomaterials **11**, 3325 (2021).