A Bardeen-Cooper-Schrieffer-like Polariton Laser

Jiaqi Hu, Zhaorong Wang, Seonghoon Kim, Hui Deng — *University of Michigan, Ann Arbor, MI, USA*

Sebastian Brodbeck, Christian Schneider, Sven Höfling — *Universität Würzburg, Würzburg, Germany*

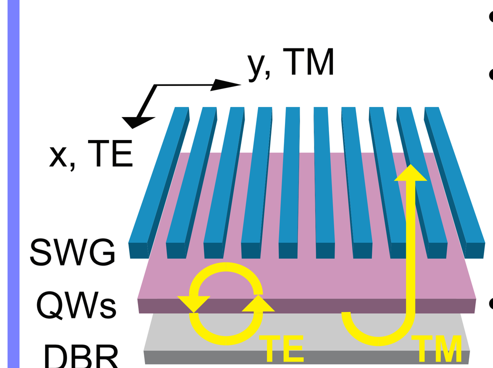
Nai H. Kwong, Rolf Binder — *University of Arizona, Tucson, AZ, USA*

Introduction

Microcavity exciton polariton systems can have a wide range of macroscopic quantum effects [1]. Polariton Bose-Einstein condensation (BEC) and photon lasing have been widely accepted in the limits of low and high carrier densities, but identification of the expected Bardeen-Cooper-Schrieffer (BCS) state at intermediate densities remains elusive. While all three phases feature coherent photon emission, essential differences exist in their matter media. Most studies to date characterize only the photon field.

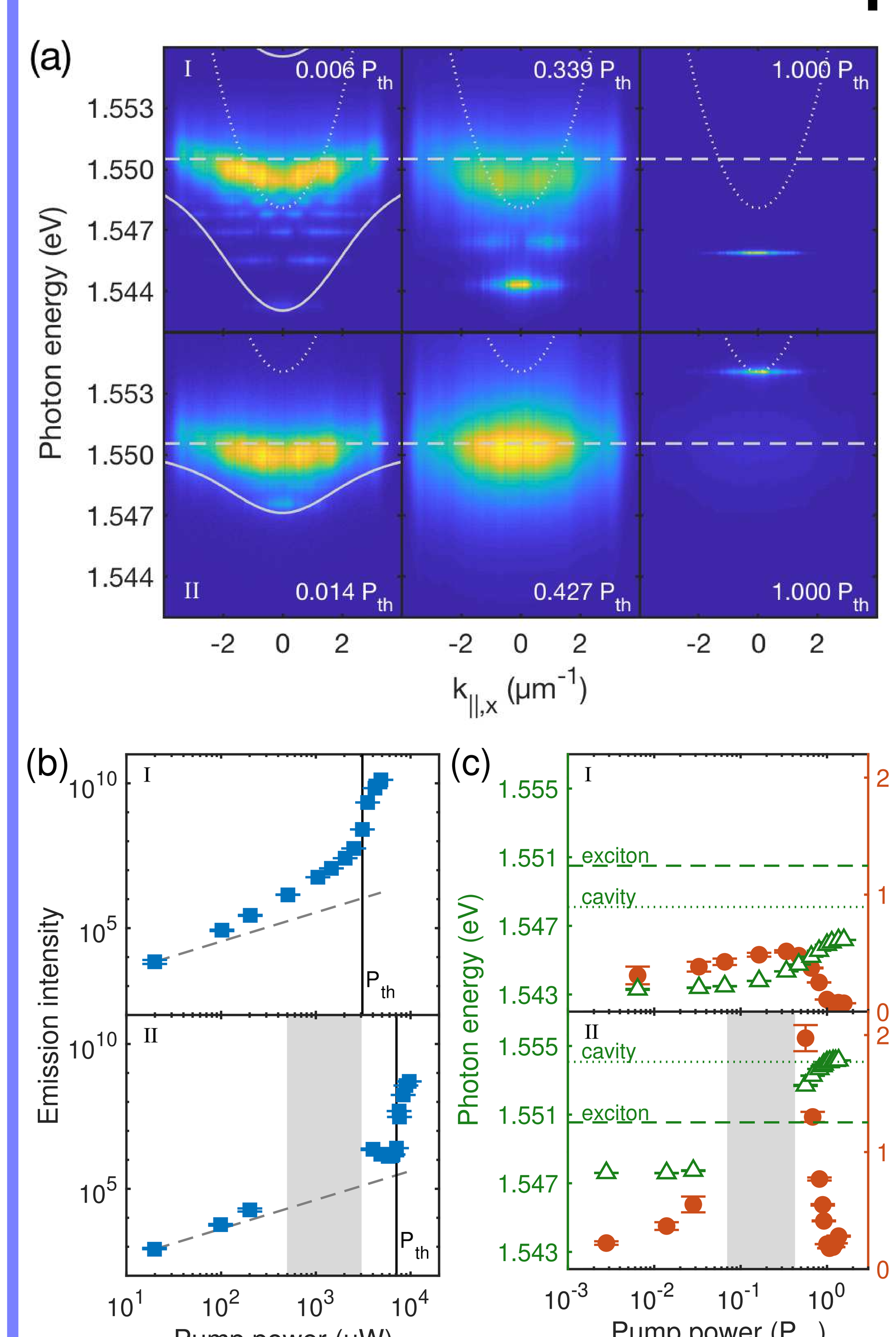
Here, using a microcavity with strong- and weak-couplings co-existing in orthogonal linear polarizations, we directly measure the electronic gain in the matter media of a polariton laser, demonstrating a BCS-like polariton laser above the Mott transition density. Theoretical analysis reproduces the absorption spectra and lasing frequency shifts, revealing an electron distribution function characteristic of a polariton BCS state but modified by incoherent pumping and dissipation.

Subwavelength Grating-Based Microcavity



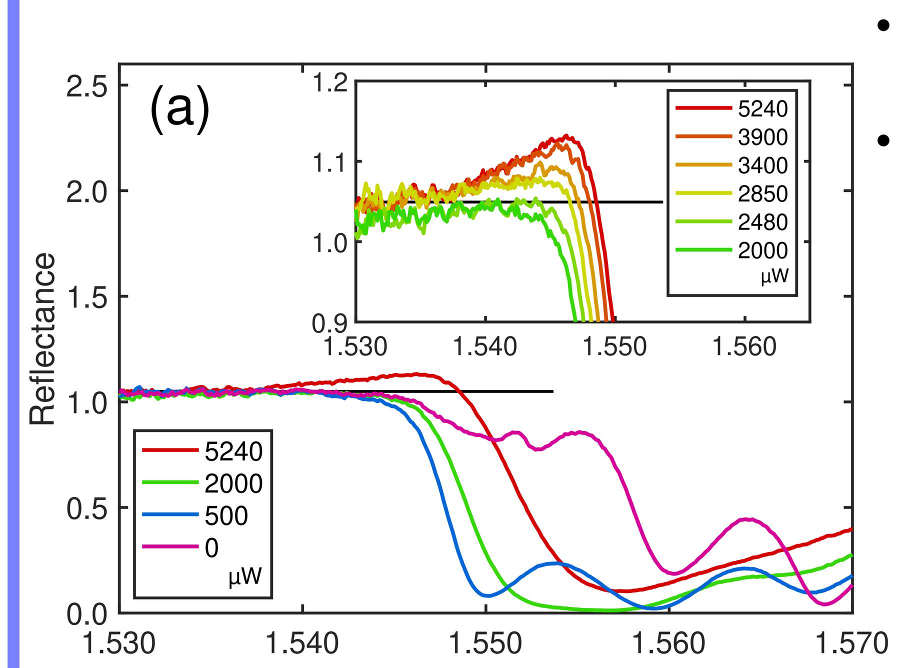
- Three sets of four 12 nm GaAs/AlAs quantum wells
- Subwavelength grating [2] as top mirror
  - Polarization selectivity
    TE – high reflectivity, strong-coupling
    TM – low reflectivity, weak-coupling
- Shared electron-hole reservoir for both polarizations under non-resonant optical pump – direct access to electronic component in the presence of lasing

Emission Spectra



- Photoluminescence in TE polarization
- Two types of lasing transition observed
- Type I (upper row):
  - Negative to small positive detuning
  - Continuous blue-shift with small broadening
  - Lasing frequency well below cavity
  - Similar to typical polariton BEC
- Type II (lower row):
  - More positive detuning
  - Very large broadening below threshold (shaded region in figure)
  - Lasing near cavity resonance frequency
  - Similar to typical photon laser
- **Type I lasing distinguished from photon laser**

Reflection Spectra

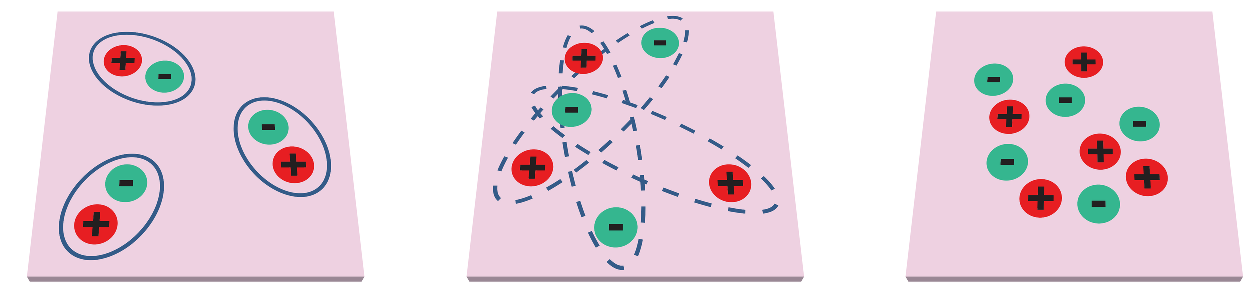


- Reflection measurement with a pulsed probe laser
- TM-polarized spectra of Type I lasing showing:
  - Mott transition – discrete exciton resonance turning into an absorption edge
  - Optical gain – peak in the spectra above unity when pump power is higher than lasing threshold, implying population inversion
- **Type I lasing also different from polariton BEC**

Acknowledgements

J.H., Z.W., S.K., and H.D. acknowledge financial support from the US Air Force Office of Scientific Research under grant FA9550-15-1-0240 and the US NSF under grant DMR 1150593. The Würzburg group gratefully acknowledges support by the state of Bavaria. N. H. K. and R. B. acknowledge financial support from the US NSF under grant ECCS-1406673 and CPU time at the University of Arizona HPC Center.

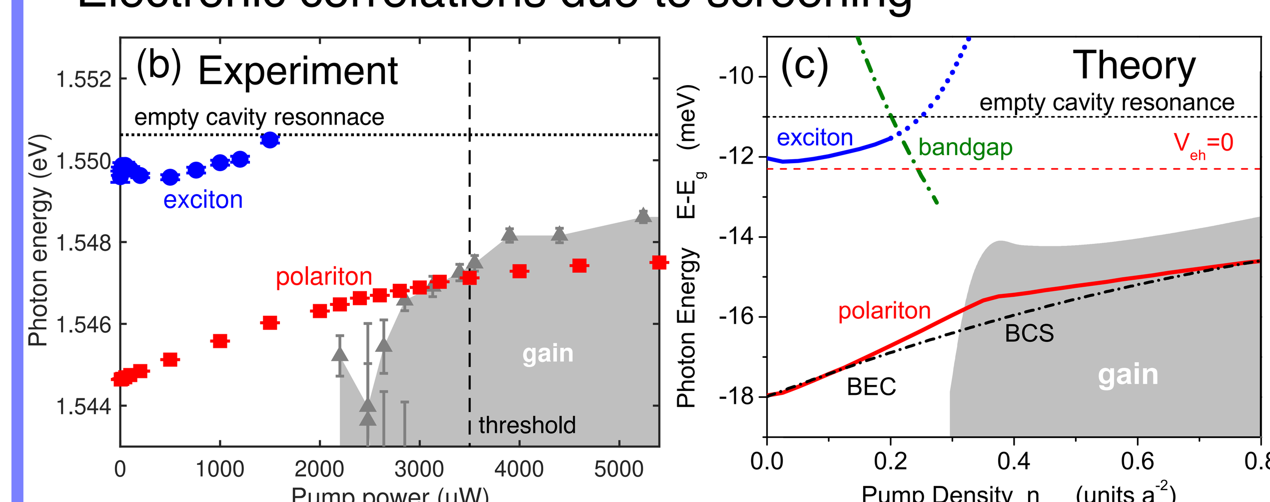
Different Types of Lasing Transition



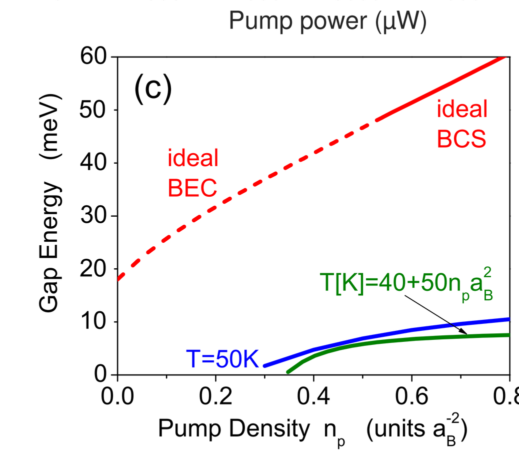
	Polariton BEC	Polariton BCS	Photon laser
Transition	⟷ smooth crossover		⟷ smooth crossover
Carrier density	$n \ll n_{Mott}$	$n \geq n_{Mott}$	$n \gg n_{Mott}$
Electron, hole distribution	far below degeneracy, no inversion	below Fermi degeneracy, small inversion	Fermi degenerate, strong inversion
Gain type	bosonic	fermionic	fermionic
Emission frequency	below cavity	below cavity	close to cavity
Coherence formation	stimulated scattering into exciton-polariton	stimulated scattering into polariton BCS	stimulated emission into a cavity mode
Quasi-particle	exciton-polariton with bound exciton	e-h-polariton with bound e-h pair	e-h plasma, unbound
Excitation spectrum	gap, by exciton binding & photon coupling	BCS-like gap by e-h pairing & photon coupling	gap possible (light-induced spectral hole)

Theoretical Results

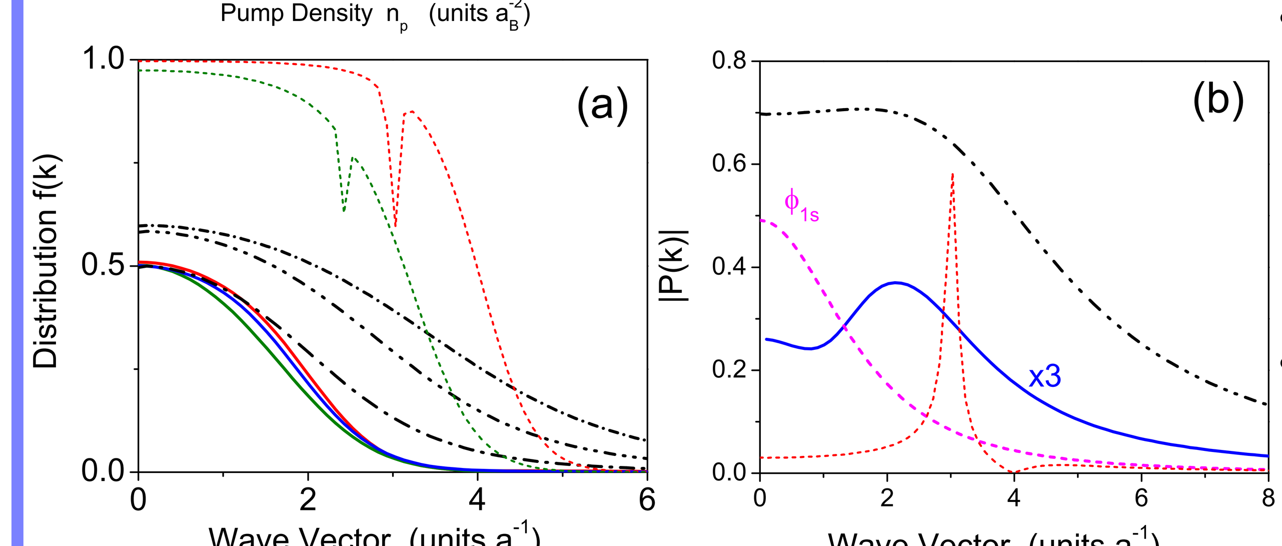
A fermionic theory for the open dissipative and pumped system
- Realistic electronic band structure
- 2-dimentional Coulomb potential
- Electronic correlations due to screening



Frequency shift and onset of gain reproduced by theory



Pair-breaking excitation energy $2 \min E^{xc}(k)$ is substantially smaller than that in the ideal system, which is expected due to cavity dissipation and dephasing.



Compare with:
- Ideal polariton BCS [3,4] – closed, quasi-equilibrium, T=0, HF approximation
- Photon laser – electron-hole interaction turned off

	distribution function $f(k)$	interband polarization $\|P(k)\|$
ideal BCS (dash-dotted lines) or BCS-like polariton laser (solid lines)	saturation near 0.5	broadly distributed
photon laser (dashed lines)	close to 1, kinetic hole burning possible	sharply peaked

Theoretical results reveal the similarities with ideal polariton BCS and the role of e-h interaction.

Conclusion

We demonstrate a BCS-like polariton lasing state. It is different from a photon laser by the preservation of a bound state manifested in spectral features including an emission linewidth that remains narrow and an emission frequency well below the cavity or exciton resonance. However, we unambiguously distinguish our system from a BEC-like state by measurement of the absorption spectra of the electronic reservoir, showing our polariton laser is formed above the Mott density and the gain is provided by inverted electronic bands. The experimental observations are described quantitatively by a fermionic theory showing electron distributions and interband polarization that are qualitatively similar to the zero-temperature polariton BCS states.

References

[1] J. Keeling, *et al.*, Semicond. Sci. Technol. **22**, R1-R26 (2007).
[2] B. Zhang, *et al.*, Light Sci. App. **3**, e135 (2014).
[3] K. Kamide and T. Ogawa, Phys. Rev. Lett. **105**, 056401 (2010).
[4] T. Byrnes, *et al.*, Phys. Rev. Lett. **105**, 186402 (2010).