AFRL-AFOSR-VA-TR-2019-0279

Coherent, Efficient and Practical Polariton Lasers Using a Designable Cavity

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09/19/2019
Final Report

Air Force Research Laboratory
AF Office Of Scientific Research (AFOSR)/RTB1

Arlington, Virginia 22203
Air Force Materiel Command

REPORT DOCUMENTATION PAGE

Form Approved
OMB No. 0704-0188

1. REPORT DATE *(DD-MM-YYYY)*
19-09-2019

2. REPORT TYPE
Final Performance

3. DATES COVERED *(From - To)*
15 Jul 2015 to 14 Jul 2018

4. TITLE AND SUBTITLE
Coherent, Efficient and Practical Polariton Lasers Using a Designable Cavity

5a. CONTRACT NUMBER

5b. GRANT NUMBER
FA9550-15-1-0240

5c. PROGRAM ELEMENT NUMBER
61102F

6. AUTHOR(S)
Hui Deng

5d. PROJECT NUMBER

5e. TASK NUMBER

5f. WORK UNIT NUMBER

7. PERFORMING ORGANIZATION NAME(S) AND ADDRESS(ES)
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503 THOMPSON ST
ANN ARBOR, MI 48109-1340 US

8. PERFORMING ORGANIZATION REPORT NUMBER

9. SPONSORING/MONITORING AGENCY NAME(S) AND ADDRESS(ES)
AF Office of Scientific Research
875 N. Randolph St. Room 3112
Arlington, VA 22203

10. SPONSOR/MONITOR'S ACRONYM(S)
AFRL/AFOSR RTB1

11. SPONSOR/MONITOR'S REPORT NUMBER(S)
AFRL-AFOSR-VA-TR-2019-0279

12. DISTRIBUTION/AVAILABILITY STATEMENT
A DISTRIBUTION UNLIMITED: PB Public Release

13. SUPPLEMENTARY NOTES

14. ABSTRACT
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Coherence properties are what distinguish a laser from other source of light and what make a laser useful. We have demmonstrated a polariton laser with coherence reaching the intrinsic limit of single-mode matter-wave lasers for the first time. We have demonstrated intensity coherence at the shot-noise limit expected of an ideal coherent state (Fig. 1, left), and phase coherence revealing interactions within the polariton condensate due to its matter-wave nature (Fig. 1, right). The work was published in Coherent Polariton Laser, Phys. Rev. X 6, 011026 (2016), and was discussed in Focus: Polariton Laser Upgrade, Physics 9, 27 (2016) and Toward a Better Polariton Laser, Optics & Photonics News, March 2016.

15. SUBJECT TERMS
polariton, laser, hybrid photonic crystal cavity, optical computing, quantum mechanics

16. SECURITY CLASSIFICATION OF:			17. LIMITATION OF ABSTRACT	18. NUMBER OF PAGES	19a. NAME OF RESPONSIBLE PERSON
a. REPORT	**b. ABSTRACT**	**c. THIS PAGE**			ROACH, WILLIAM
Unclassified	Unclassified	Unclassified	UU		**19b. TELEPHONE NUMBER** *(Include area code)*

Standard Form 298 (Rev. 8/98)
Prescribed by ANSI Std. Z39.18

FINAL REPORT DOCUMENT for FA9550-15-1-0240

Title: Coherent, Efficient and Practical Polariton Lasers Using a Designable Cavity
Report Period: 7/15/2015-7/14/2018
Principal Investigator: Hui Deng, University of Michigan, Ann Arbor

In this project, using a designable hybrid photonic crystal cavity (HPCC) polariton system, we have contributed to fundamental understanding and technological innovation in semiconductor photonics. We describe below three of the most important contributions first followed by another four significant contributions on the experimental and theoretical fronts.

I. Coherent polariton laser [Phys. Rev. X 6, 011026 (2016)]

Coherence properties are what distinguish a laser from other source of light and what make a laser useful. We have demmonstrated a polariton laser with coherence reaching the intrinsic limit of single-mode matter-wave lasers for the first time. We have demonstrated intensity coherence at the shot-noise limit expected of an ideal coherent state (Fig. 1, left), and phase coherence revealing interactions within the polariton condensate due to its matter-wave nature (Fig. 1, right). The work was published in “Coherent Polariton Laser”, Phys. Rev. X 6, 011026 (2016), and was discussed in “Focus: Polariton Laser Upgrade”, Physics 9, 27 (2016) and “Toward a Better Polariton Laser”, Optics & Photonics News, March 2016.

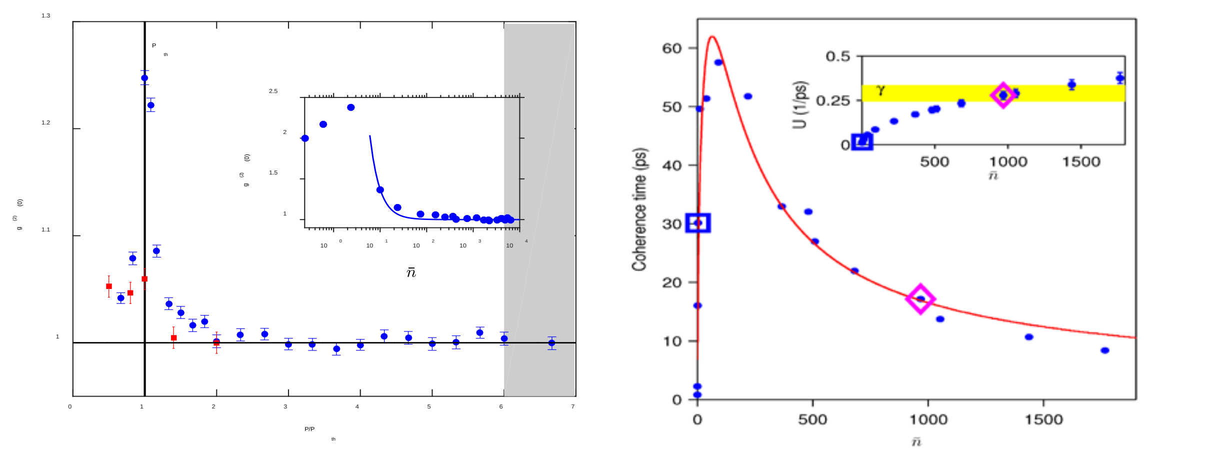


Fig 1. Left, Second-order auto-coherence function $g^{(2)}(0)$ vs. the normalized excitation power. It measures the intensity noise of the polariton laser, which shows a sharp decrease above the threshold to the shot-noise limit of 1. Large fluctuations around the thresold relfects relaxation oscillation. The blue (red) data correspond to pulsed (continuous wave) excitation. The inset is the corrected for the time-resolution of the photo detectors and the blue line is a theoretical fit. The grayed area corresponds to weak-coupling regime.
Right: Phase coherence time vs. the polariton number in the lasing mode. It is obtained from first-order coherence measurements. A sharp increase of the coherent time was seen near threshold as expected in typical lasers. The decrease of the coherence time at large polariton number, while maintaining shot-noise limited intensity noise, results from interactions among polaritons in the lasing mode.

II. Matter-wave frequency comb generation from dissipatively coupled polariton condensates. [Manuscript under review at Nature Physics]

We demonstrated a new mechanism of frequency comb generation using coupled polariton condensates. It results from the dynamic interplay between on-site nonlinearity and inter-site couplings. This is distinct from other systems, such as microtoroidal resonators and quantum cascade lasers that are based on cascaded four-wave mixing process. A unique feature of this form of frequency comb generation is that the comb spacing is not given by the cavity transverse mode spacing and can be engineered from GHz to THz without having to drastically change the physical dimension of the system. Furthermore, since it is based on polariton condensation, the polariton comb allows a very low threshold and an incoherent pump, including electrical injection.

The matter-wave frequency comb is created using the designable HPCC cavity with a suspended high-contrast grating mirror, which allows us to create two coupled condensate and engineer their interaction and coupling via deformation of the suspended mirrors. We obtained extensive experimental and theoretical evidences to support the results, including spectroscopy and interferometric measurements showing equidistant frequency lines and characteristic phase relations between the two coupled condensates (Fig. 2).

The work paves the way for future development and optimization of low threshold optical frequency comb sources, and will open doors to other novel phenomena and device concepts based on dissipatively-coupled nonlinear cavity systems.

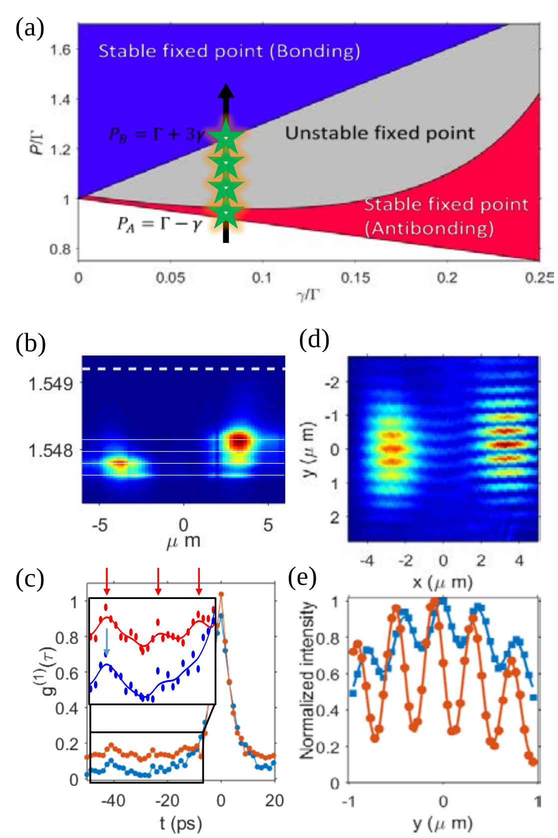


Fig. 2. (a) A bifurcation diagram of the coupled polariton system in the parameter space of pump rate P vs. dissipation coupling rate γ, normalized by the cavity decay rate Γ. The standard lasing threshold is when $P/\Gamma = 1$ in the absence of dissipative coupling. For finite dissipation γ, thresholds for stable and unstable fixed-point solutions emerge with increasing pump, as indicated by the arrow. (b) The real space spectrum showning bifurcation from the bonding and anti-bonding states into four frequencies as marked by the solid white lines. All four freuqencies are well below and distinct from the next excited state of the cavity system as marked by the white dashed line. (c) Time-domain first order coherence from the two sites (red and blue symbols denotes the left and right site respectively). Both sites show oscillations due to the multiple frequency components and agree well with simulations (not shown here). (d) Measurement of the relative phase between the two site by spatial interference with a reference beam. (e) Fringes obtained from (d) for the two sites (red and blue symbols respectively), showing both different intensities and a relative phase displacement of $\Delta\phi = 0.51 \pm 0.08\,\pi$, as expected for the frequency comb state. In contrast, stable bonding or anti-boding state lasing should feature equal intensity between the two sites and a phase difference of $\Delta\phi = 0$ or π, as we observe at lower or igher pump rates (not shown here).

III. A Bardeen-Cooper-Schrieffer Polariton Laser [Manuscript under review at Nature]

We demonstrated the first polariton laser in the Bardeen-Cooper-Schrieffer (BCS) regime, which is also the first demonstration of the particle-hole type BCS state as well as matter-light hybrid BCS state. It validates and pushes forward many decades of theoretical efforts on this subject.

Both the BEC and BCS states were postulated in excitonic systems half a century ago. Research on exciton- and especially polariton-BEC has exploded in the past decade, with a large part of the community accepting spectral features as experimental evidence of a polariton BEC despite persistent skepticism. BCS has been considered much more difficult to achieve, and no experimentally accessible hallmark signatures have been identified.

In our HPCC polariton system, both the weakly and strongly cavity-coupled excitons coexist and share the same hot carrier reservoir, enabling access to the electronic media at the presence of polariton lasing. In what would have been commonly accepted as a polariton BEC, we measure directly fermionic gain and population inversion (Fig. 3), unambiguously distinguishing it from a polariton BEC. We also show stark contrast in spectral properties between the BCS polariton laser and a conventional photon laser, thereby unambiguously distinguishing it from the commonly known photon laser. A theory based on extended semiconductor Bloch equation reproduces the experimental results and in turn reveals the BCS nature of the new manybody phase.

Our findings challenges the previous understanding and experimental interpretation of polariton BEC while at the same time reconfirm that strong electronic correlations underline phenomena so far associated with polariton BEC.

The finding is also significant on the technological front. Semiconductor lasers have been a revolutionary technology in the 20th century. It is by now ubiquitous in our daily lives. Our work is an important progress on the foundation of semiconductor lasers. It demonstrates a new mechanism of lasing, providing new insight on the proper understanding of the lasing mechanism as we advance the semiconductor laser technology, especially as we push for lasers of higher energy efficiency and intensity, and as materials with inherently strong matter-light interaction become available, such as two-dimensional materials and organic crystals.

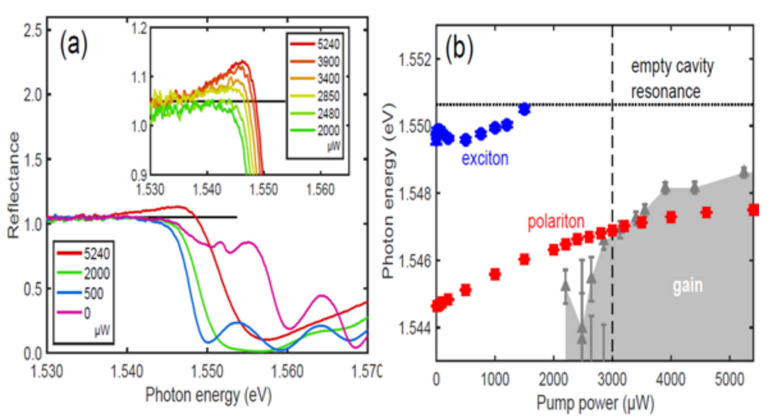


Fig. 3. Gain and energetic positions of a BCS polariton laser. (a) Reflection/absorption spectra of the electronic reservoir at different pump powers, showing clearly gain, above the reference level of unity marked by the black lines. Inset: zoom-in near the gain. (b) Pump power dependence of the energetic positions of the polariton ground state (red squares), the exciton (solid blue circles) and upper spectral-bound of gain (grey triangles). The BCS polariton lasing threshold (black dashed line) coincides with the onset of the fermionic gain.

IV. Monolithic high-contrast grating based polariton laser [Manuscript under review at ACS Photonics]

We demonstrate a new type of vertical-cavity for polariton lasers and VCSELs. It incorporates a monolithic high-contrast grating (MHCG) mirror to allow phase engineering and mode control on a compact and practical platform.

High-contrast grating (HCG) mirrors have been intensively studied to replace distributed Bragg reflectors for microcavity applications, for they allow design flexibility unavailable with DBRs in addition to a compact size. Typically HCGs are suspended in air in order to achieve sufficient reflectance for lasing action. Such HCGs are fragile to make and to use. Electrical injection, thermal dissipation and mechanical instability all pose challenges. Non-suspend, MHCGs were proposed, but so far, high reflectance has only been shown theoretically and no cavities have been constructed with MHCGs.

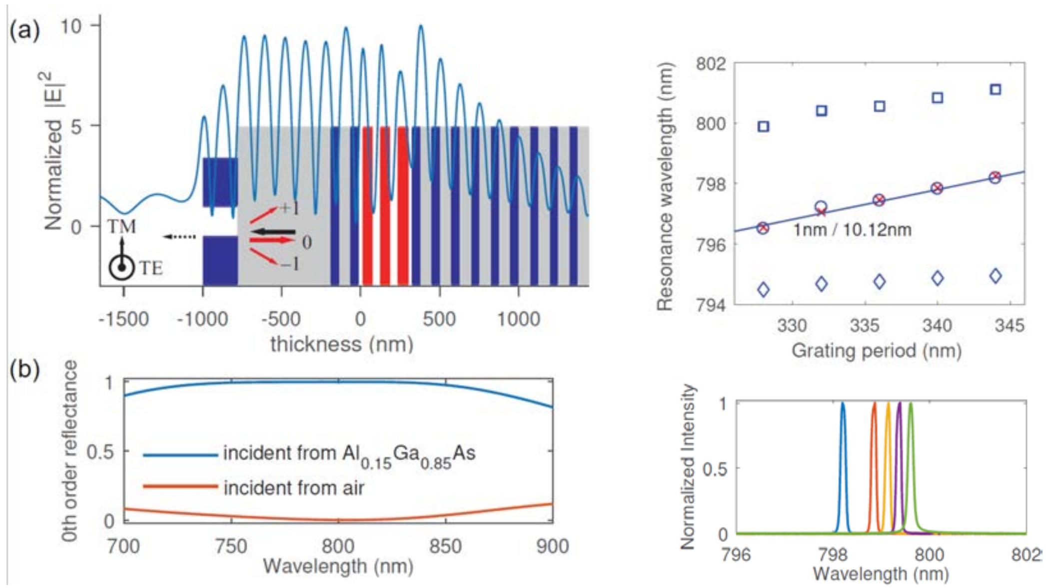


Fig. 5 (a) A schematic of the sample structure and the simulated TM-polarized electric field intensity profile (blue line). The sample consists of from left to right: a Al0.15Ga0.85As MHCG (blue), a Al0.85Ga0.15As spacer (grey), 1.5 pairs of top DBR made of Al0.15Ga0.85As/Al0.85Ga0.15As (blue/grey), an AlAs cavity (white) with three stacks of GaAs QWs (red), and a bottom DBR. Light incident on the MHCG from inside the cavity (marked by the black arrow) will mostly be reflected (thick red arrow) with a small fraction diffracted to higher order modes (thin red arrows), while transmission is negligible (black dotted arrow). (b) Simulated 0th order reflectance of MHCG, showing high asymmetry for light incident from the two sides of the MHCG. MHCG is highly reflective for the TM-polarized light incidence from the cavity side (blue) but shows low reflectance for light incident from air (red). (c) Tuning of the cavity and polariton resonance with the MHCG parameters. The measured lower and upper polariton resonances (open diamonds and square, respectively) at low pump powers and the corresponding cavity resonances as a function of the grating period. The cavity resonance obtained from the measured lower and upper polaritons and exciton resonances are marked by the open circles, while the simulated cavity resonance are marked by the red crosses. The solid line is a linear fit to the experimental cavity resonance vs period, showing tuning of the cavity resonance with the grating period at 1 nm/10.12 nm. (d) Tuning of the polariton laser wavelength by the MHCG grating parameter. The emission spectra of the polariton laser at high pump powers for the corresponding MHCGs as in (c).

We report here the first high-quality VCSEL using MHCG mirrors (Fig. 5). We observe not only strong coupling between excitons and cavity photons but also polariton lasing. Furthermore, we demonstrate tuning of the lasing wavelength by controlling the grating parameters, such as the grating period and duty cycle (Fig. 5c-d).

The new MHCG-VCSELs offer the key advantages of the conventional HCG, including phase engineering, compact size, and lateral integration, with a drastically simplified fabrication process on a much more robust platform. Integration with electrodes would also be straightforward due to a direct current injection path unobstructed by an air gap or other insulating layers. They should greatly facilitate future research and device development using meta-surfaces in microcavity.

V. Optimizing the cavity design of planar polariton systems [Wang, APL 6, 061102 (2017)]

An optimal cavity is crucial for polariton research. The key figures of merit a strong vacuum field strength (E) at the quantum well plane and a high cavity quality factor (Q). A strong vacuum field leads to stronger exciton-photon coupling and thus a larger vacuum Rabi splitting between polariton modes. A high quality factor leads to a long lifetime and coherence time of the cavity photon and correspondingly the polariton. They together enable robust polariton modes, thermodynamic formation of quantum phases, and polariton lasers with lower density threshold at higher operating temperatures.

We demonstrated how to optimize different types of cavities for the strongest field and compared their polariton splitting, quality factors, and practicality for fabrication. In particular, we find that HPCC cavities may allow simultaneously a stronger field and high Q (Fig. 4).

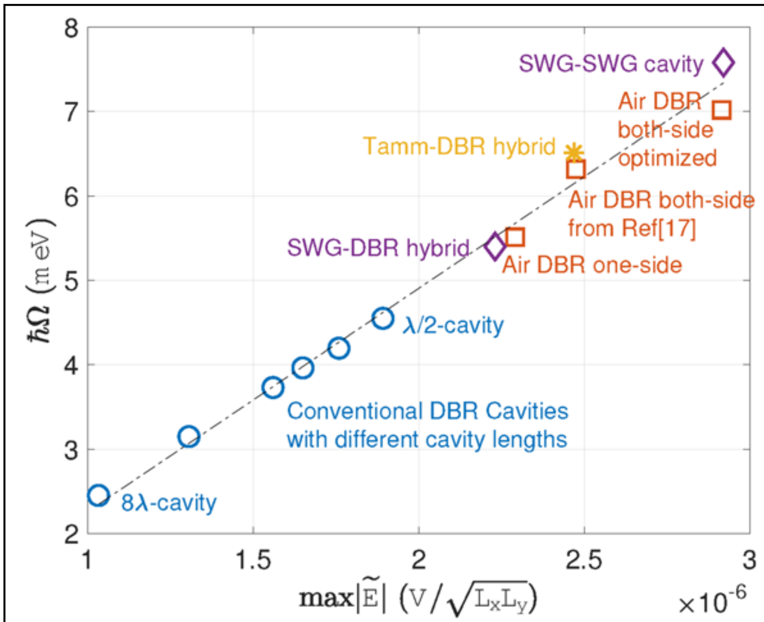


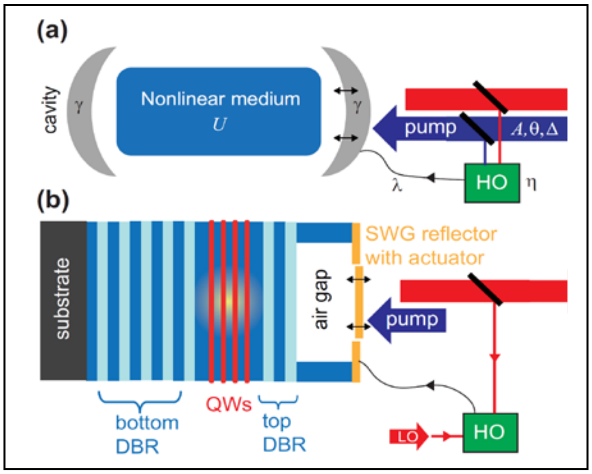
Fig 4. Calculated vacuum Rabi splitting and maximum vacuum field strength for various optimized cavities. All cavities are based on the III-As material system. A single quantum well is embedded at the field maximum.

The dashdotted line is a linear fit through all points, showing the linear relation between Rabi splitting and the properly normalized cavity field strength.

The HPCC cavity, marked as SWG-DBR hybrid, is made of an SWG top mirror and a DBR bottom mirror. It has significantly higher Rabi splitting than the best DBR-DBR cavity. Tamm-DBR or Air-DBR cavities have higher Rabi splitting but have relatively low quality factor, are hard to fabricate, and polariton lasing has not been possible in them so far.

VI. Non-classical light generation from polaritons [Joana, PRA 94, 063802 (2016)].

We investigated theoretically with our collaborators non-classical light generation using the polariton system. Steady state coherent light with negative Wigner functions can be generated from a polariton system, taking advantage of its nonlinearity. Phase stabilization via external feedback is still necessary, which needs in situ tuning of the cavity frequency. HPCC allows such tuning via electro-mechanical control of the suspended grating mirror. An illustration of the proposed experimental scheme is shown in figure to the right.



VII. Cooperative emitter-light coupling in any dimension [Hill, PRA 95, 033832 (2017)]

We developed a theory of cooperative light scattering valid in any dimension d: connecting theories for an open line, open plane, and open space in the nonrelativistic regime. This theory includes near-field and dipole-orientation effects, highlighting how field-mode confinement controls the phenomena. We find that 2D has the most complex orientation dependence between dipoles with subwavelength separations. This complex dependence is due to the lack of cylindrical symmetry with respect to the separation between dipoles, different from both 3D and 1D.

The theory readily reveals scaling behavior of the coupling in different diemsnions, as shown by the coupling ($\tilde{\omega}_{ij}$) and decay coeffecients ($\tilde{\gamma}_{ij}$) vs. d and $\tilde{r}_{ij} = r_{ij}/\lambda$ (the normalized emitter seperation) in the right figure. It provides intuition into how superradiance can be controlled via field confinement, orientation, and emitter placement.