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An Ultrafast Electrical and Optical Excitation Systemfor Research on Polaritons in Hybrid Cavities for Scalable Quantum Photonics

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Final Report

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In this DURIP program, we have acquired the equipment to have assembled a versatile system for ultrafast optical and electrical modulation and excitation of semiconductor polaritons (half-light half-matter particles in semiconductor microcavities), for the research of nonlinear and quantum
photonic phenomena and novel photonics devices based on coherent matter-waves. The full system consists of three major parts that are integrated
together: cryogenic systems with custom-designed sample chambers and sample holders to allow optical access, electrical control, and required
thermal and mechanical stability, an ultrafast electrical system with capability of ultrafast electrical excitations with >10 GHz bandwidth and less than 10 ps jitter, and an ultrafast pulsed optical excitation and detection system. The complete integrated system enables versatile excitation and
measurement capabilities unavailable before at Michigan for the microcavity polariton based quantum photonics.

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An Ultrafast Electrical and Optical Excitation System for Research on Polaritons in Hybrid Cavities for Scalable Quantum Photonics

Report Period: **9/15/2015-9/14/2017**

Principal Investigator: **Professor Hui Deng**

Institution: **University of Michigan**

Award number: **FA9550-15-1-0366**

In this DURIP program, we have acquired the equipment and assembled a versatile system for ultrafast optical and electrical modulation and excitation of semiconductor polaritons (half-light half-matter particles in semiconductor microcavities), for the research of nonlinear and quantum photonic phenomena and novel photonics devices based on coherent matter-waves.

The full system consists of three major parts that are integrated together:

- Cryogenic systems that keep the device down to the liquid helium temperature while at the same time allow optical access and electrical control.
- An ultrafast optical excitation and detection system.
- An ultrafast electrical excitation and detection system.

The cryogenic systems consist of closed-cycle cryostats with custom designed sample chambers or sample holders with required optical and electrical access. Shown in Fig. 1 are drawings of the Montana cryostat with a custom top-castle chamber and sample holder. The system is designed to allow optical spectroscopy in both reflection and transmission configurations. Importantly, both configurations allow short working distances of a few millimeters, so as to allow wide k-range for Fourier space imaging and high spatial resolutions for micro-photoluminescence at near-infrared. At the same time, the sample can be translated with sub-micron resolution over a large area of about 20 centimeters by 20 centimeters. The sample holder is also electrically wired to allow electrical probe options. The sample is maintained in a vibration free environment with high temperature stability (Fig. 2).

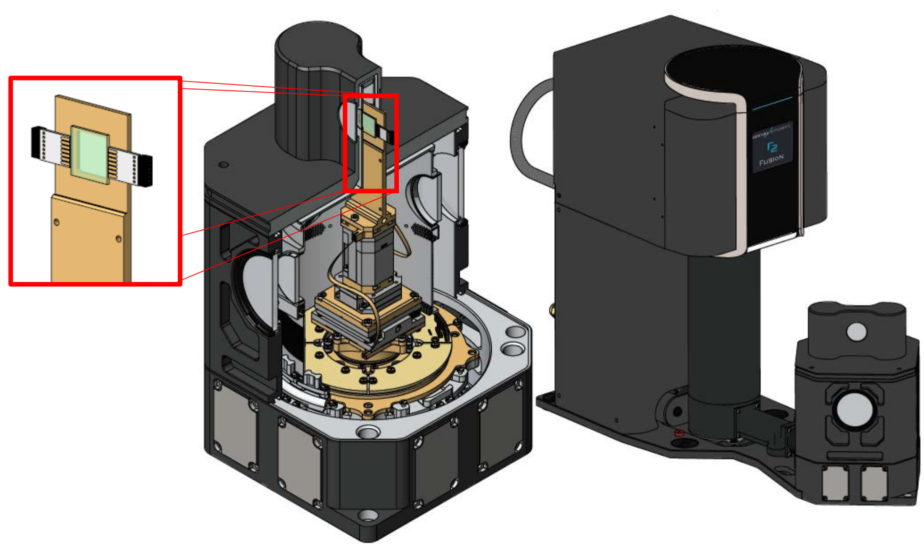

Fig. 1. Drawing of the closed-cycle cryostat from Montana Instrument with a custom-designed top-castle as the sample chamber and, as shown in the red box, a custom-designed sample holder with electrical wiring options.

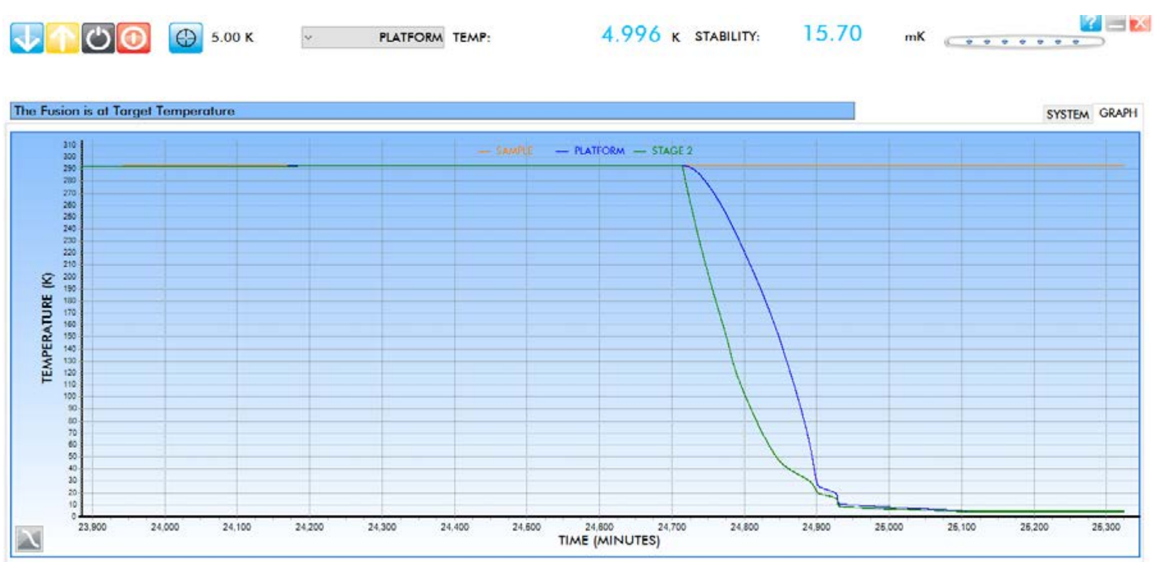

Fig. 2. An example test result of the cool-down performance and temperature stability of the cryostat, showing a cool-down time of about four hours and temperature stability of 15.7 mK at 5 K.

The ultrafast electrical pulse generation system consists of two main parts: 1. a clock generator (Stanford research system CG635) which is used to generate a square pulse of desired frequency and peak-to-peak voltage, and 2. an electrical pulse generator (Alnair labs EPG-200) triggered by the clock generator and generates electrical pulses with pulse widths of <100ps at the clock frequency. In addition, to electrically drive a sample, it is important to control the amplitude and the DC bias of the electrical pulses. Thus the amplitude of the pulse is controlled by an amplifier and the DC bias is controlled by the source meter unit (SMU). A bias tee is used to combine the DC and AC components. Detection is performed by an oscilloscope. A schematic of the system is shown in Fig. 3. Example images of the clock generator and the electrical pulse generator pulses are shown in Fig. 4. Figure 5 shows the typical amount of jitter the electrical pulses have, which is on the order of 10 ps. The system will enable the research on electrically tuned or pumped polariton lasers and polariton circuits. It will also enable us to elucidate charge dynamics fundamental to the operation of electrically pumped or controlled polariton devices.

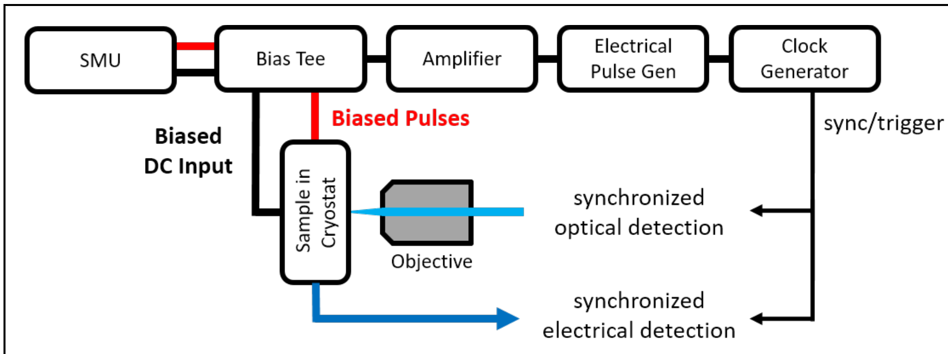

Fig. 3. A schematic of the ultrafast and DC electrical excitation system integrated with the optical and measurement systems.

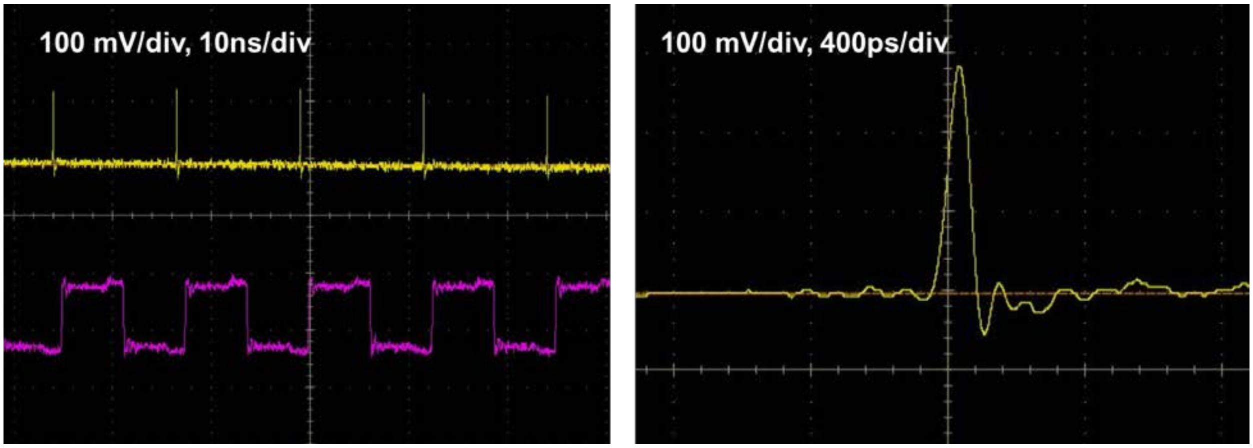

Fig. 4. Left: Square pulses at the same repetition rate of the laser of 80 MHz generated by the clock generator (in magenta) and the corresponding electrical pulses (in yellow). Right: A single electrical pulse with a half width of about 80 ps as viewed on the oscilloscope.

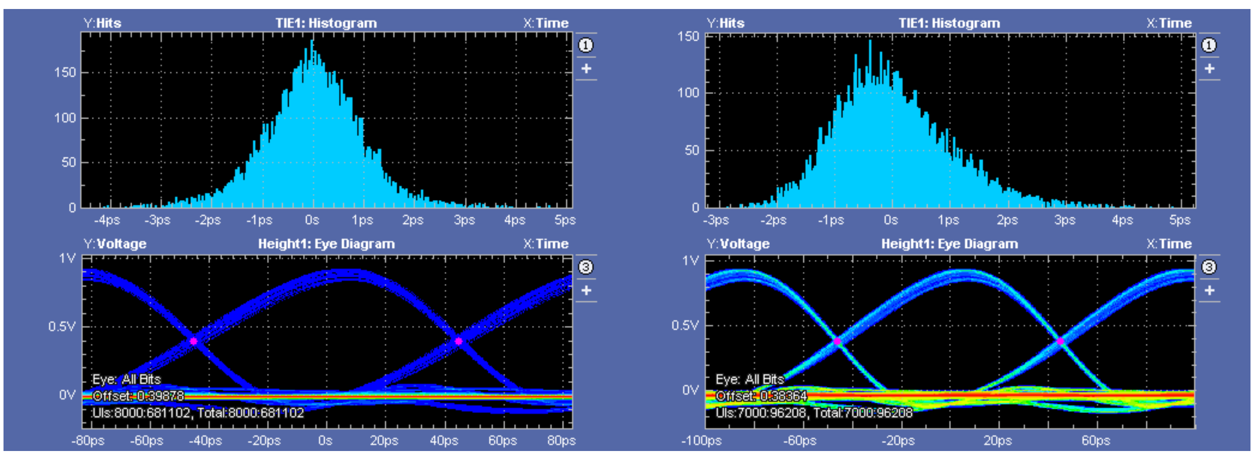

Fig. 5. Histograms and eye diagrams of the electrical pulse jitter measurement for 80MHz pulses (left) and 500MHz pulses (right), showing a very small jitter of about 10 ps.

The ultrafast optical excitation and detection system consists of a custom-built suite of optics for the cryogenic systems to control and deliver the excitation beams, and to collect the signal. It include upgrades and repairs of an existing ultrafast Ti-Sapphire laser system to achieve stable mode-locked, pulsed output of 1W to 2W output power in the near infrared spectral range. The pulse duration vary between 150 fs and 30 ps. Pump-probe capability with selectable bandwidth and variable delay is established, which enables coherent, multi-beam excitation of coupled polariton cavities for quantum light generation. Figure 6 shows a photo of the optical spectroscopy system. Figure 7 shows an example of the real-space image of a polariton quantum box and Fourier space image of a polariton quantum wire.

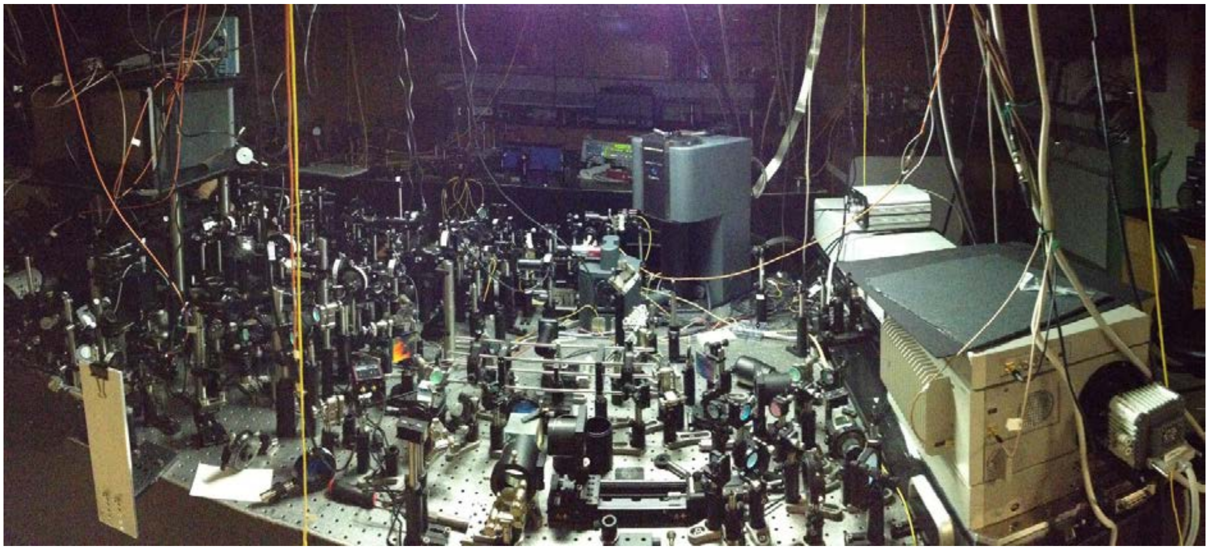

Fig. 6. A picture of the optical spectroscopy system integrated with the Montana Ins. cryostat and ultrafast excitation laser. It includes in both the excitation path and collection path control of the laser or signal beams' power, spectral width and polarization. The signal is collected by confocal-spectroscopy then sent for real-space or Fourier-space imaging selected by a flip mirror, for spectrally resolved and/or time-resolved measurements, first and second-order interference spectroscopies.

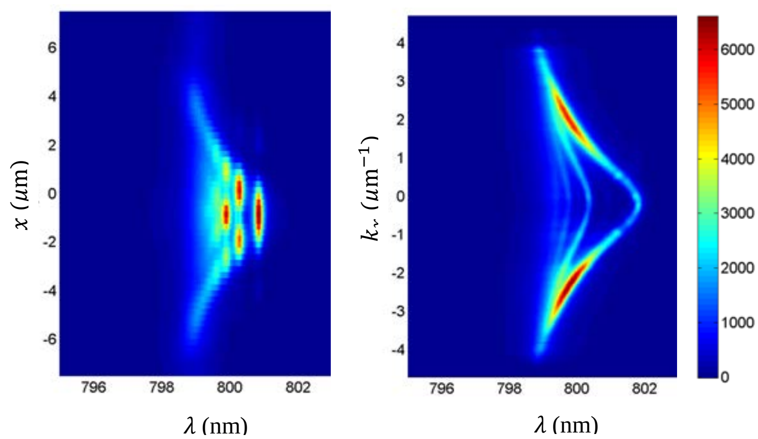

Fig. 7. Spectrally resolved real-space (left) and Fourier space (right) images of the photoluminescence from a polariton quantum box (left) and quantum wire (right), showing the respective mode structures. The color represents the emission intensity, corresponding to the distribution of the polariton population among the modes.

The complete system enables versatile excitation and measurement capabilities unavailable before at Michigan for the microcavity polariton research, and may facilitate the development of a variety of defense-related applications including lasers with ultra-low energy threshold, novel nonlinear and quantum optical devices, and efficient and ultrafast communication. The new system, apart from off-the-shelf commercial equipment, has been built mostly by graduate students and will continue to allow graduate and undergraduate students to carry out innovative experimental research on polariton based quantum photonics.

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Abstract

In this DURIP program, we have acquired the equipment to have assembled a versatile system for ultrafast optical and electrical modulation and excitation of semiconductor polaritons (half-light half-matter particles in semiconductor microcavities), for the research of nonlinear and quantum photonic phenomena and novel photonics devices based on coherent matter-waves.

The full system consists of three major parts that are integrated together: cryogenic systems that keep the device down to the liquid helium temperature while at the same time allow optical access and electrical control, an ultrafast optical excitation and detection system, and an ultrafast electrical excitation and detection system.

The cryogenic systems consists of closed-cycle cryostats with custom designed sample chambers or sample holders with required optical access, simultaneous electrical feedthroughs for excitation and measurement, and at the same time mechanical stability within about thirty nanometers and temperature stability within about 20 mK.

The ultrafast electrical system consists of an ultrafast electrical pulse generator, followed by a pulse amplifier, to provide ultrafast electrical excitation of >10 GHz bandwidth, and an ultrafast oscilloscope for measurement. It will enable the research on electrically tuned or pumped polariton lasers and polariton circuits. It will also enable us to elucidate charge dynamics fundamental to the operation of electrically pumped or controlled polariton devices.

The ultrafast optical excitation and detection system consists of a custom-built suite of optics for the cryogenic systems to control and deliver the excitation beams, and to collect the signal. It also includes upgrades and repairs of an existing ultrafast Ti-Sapphire laser system to achieve stable mode-locked, pulsed output of 1W to 2W output power in the near infrared spectral range. The pulse duration vary between 150 fs and 30 ps. Pump-probe capability with selectable bandwidth and variable delay is established, which will enable coherent, multi-beam excitation of coupled polariton cavities for quantum light generation.

The complete integrated system enables versatile excitation and measurement capabilities unavailable before at Michigan for the microcavity polariton research, and may facilitate the development of a variety of defense-related applications including lasers with ultra-low energy threshold and other novel nonlinear and quantum optical devices for efficient and ultrafast communication. The new system, apart from off-the-shelf commercial equipment, has been built mostly by graduate students and will continue to allow graduate and undergraduate students to carry out innovative, multi-disciplinary experimental research on polariton based quantum photonics.

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Supplies			
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Appendix Documents

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