Generating a Photonic Dimer for Use in a Two-Qubit Photonic Quantum Gate

Honors Capstone Student: James Kennedy
Faculty Advisor: Professor Pei-Cheng Ku; GSI: Juhyeon Kim
ENGINEERING HONORS PROGRAM
UNIVERSITY OF MICHIGAN

Introduction

- In quantum computing, a qubit can be represented as a superposition of 0 and 1.
- In photonic quantum computing, a qubit is encoded in the state of a photon.
- Single-qubit gates are trivially implemented with linear optical elements (e.g., beam splitters).
- Two-qubit gates are difficult to implement due to the weak interaction between photons.
- We are working towards developing a controlled phase gate, which depends on a two-photon bound state known as a photonic dimer.
- Generating a photonic dimer requires quantum dots, waveguides, grating couplers, etc. that must be individually verified and then assembled.

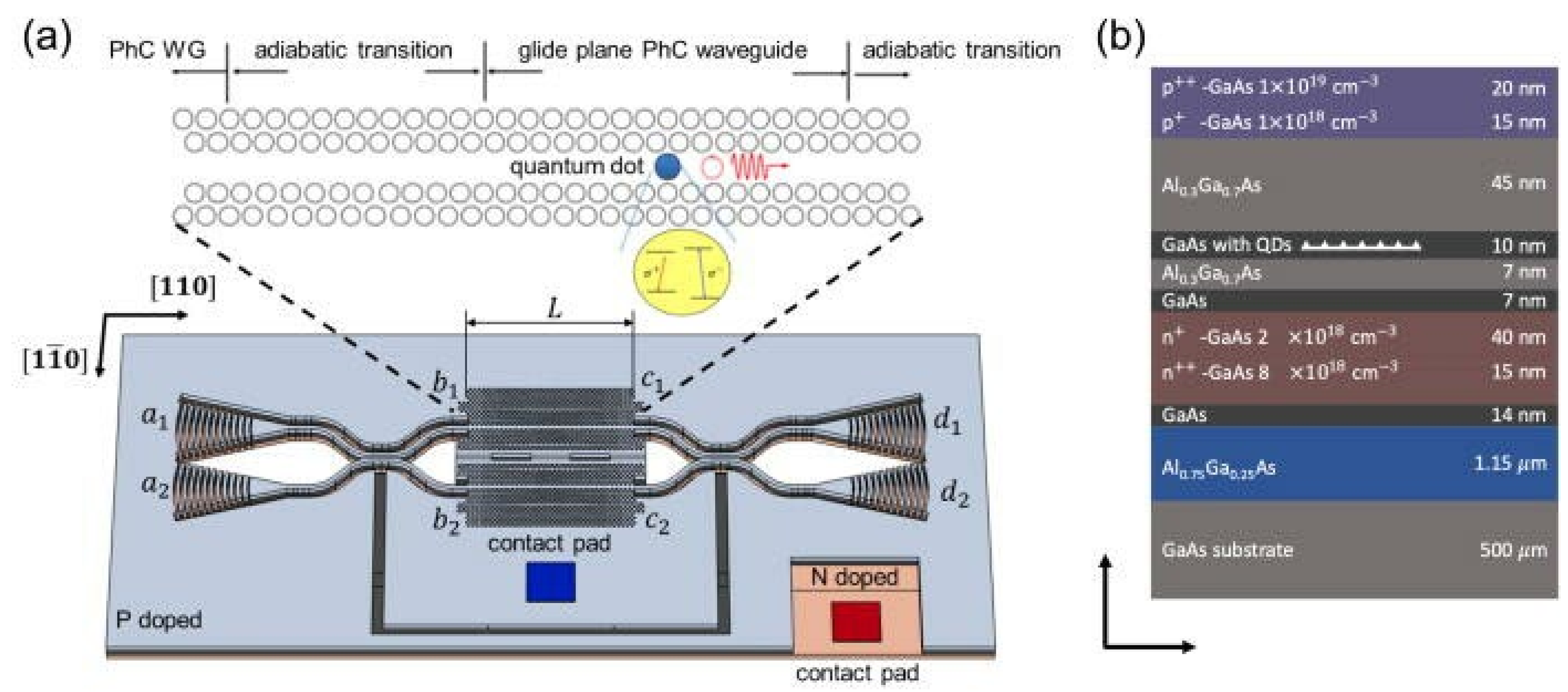
Background

- Controlled phase gate conditionally applies a phase shift to the target qubit depending on the state of the control qubit.
- Our proposed gate depends on a photonic dimer acquiring a non-trivial π phase shift upon interacting with a quantum dot.
- To confirm the generation of a photonic dimer, a Mach-Zehnder interferometer (MZI) leverages the π phase shift to orchestrate interference between photons, which can be observed at the output.
- MZI includes quantum dots, integrated waveguides, input / output grating couplers, photonic crystal, and phase modulator.

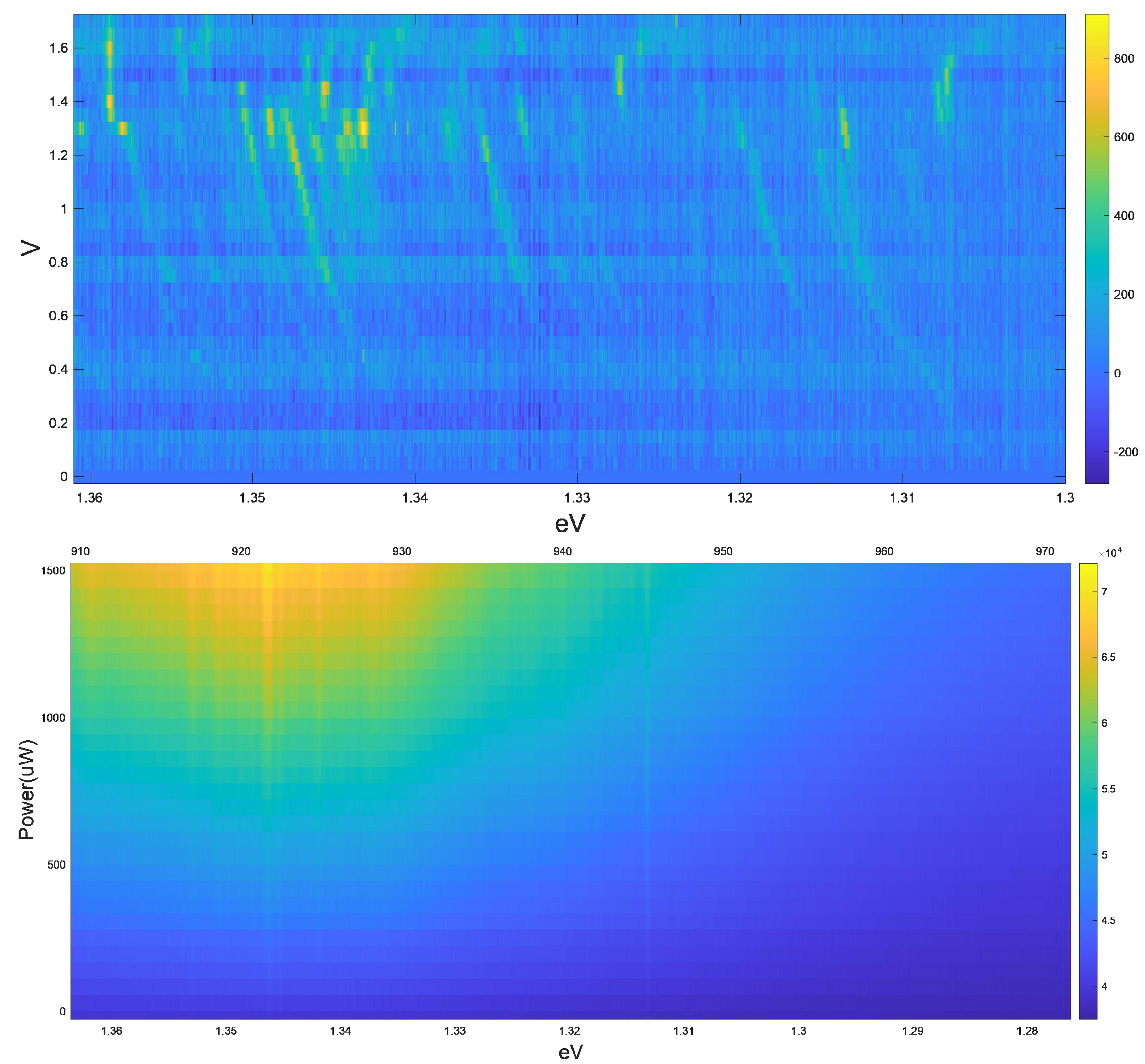
Methods

- Calibrated a spectrometer to measure the intensity of near-infrared light at high resolution.
- Loaded samples into a cryostat to enable quantum mechanical phenomena.
- Designed and optimized laser and signal paths consisting of beam splitters, mirrors, lenses, filters, polarizers, and fiber optic cables.
- Utilized a piezoelectric stage, power supply, and neutral density filter to vary position, bias voltage, and laser power respectively.
- Excited sample with a near-infrared laser and recorded the emission spectra of GaAs, InAs, and quantum dots.
- Used white light and CCD camera to image patterned samples and integrated waveguides at high resolution.

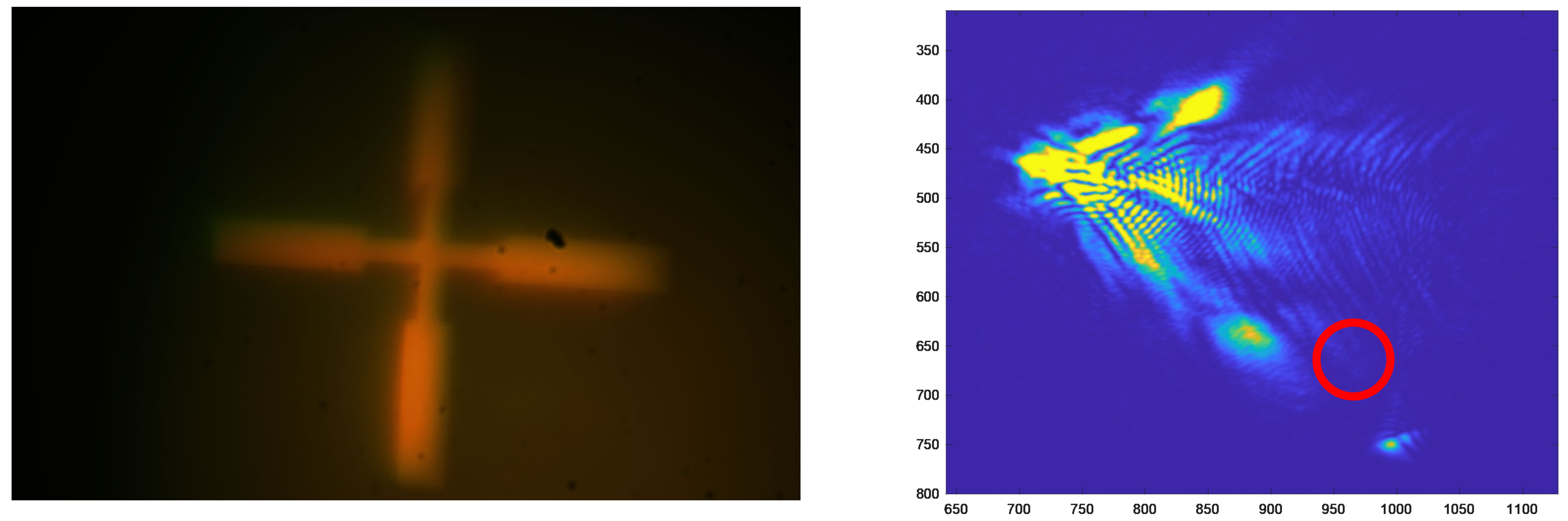
Mach-Zehnder Interferometer Experimental Setup and Material Composition [3]



Dependence of the Quantum Dot Emission Spectrum on Applied Bias Voltage and Laser Power



CCD Camera Images of Patterned Sample and Transmittance of Integrated Waveguide with Input / Output Grating Couplers



Results

- Observed the emission spectrum of multiple quantum dots embedded in the sample.
- Observed the Stark effect, or the shifting of the spectral peaks under an applied bias voltage.
- Observed excitons, biexcitons, and triexcitons as evidenced by the linear dependence of the emission spectrum on laser power.
- Captured high-resolution images of samples with features on the order of tens of microns.
- Used near-infrared laser and CCD camera to quantify the efficiency of input / output grating couplers and integrated waveguides.

Conclusion

- We can design and optimize an experimental setup to detect extremely faint signals such as the emission spectrum of a quantum dot.
- Verified the correct operation of the quantum dots, input / output grating couplers, and integrated waveguides.
- Prepared to verify the correct operation of the phase modulator, photonic crystal, and Mach-Zehnder interferometer.
- Exciting a sample with a laser and collecting the emission requires extreme precision and immense patience.
- Once a signal is found, optimizing an experimental setup is considerably easier.

Future Work

- Verify the chiral coupling of a quantum dot with a photonic crystal waveguide by directly exciting the quantum dot with a laser and measuring the emission at both ends of the waveguide.
- Determine the tolerance of the quantum dot position within the photonic crystal waveguide.
- Verify the correct operation of the phase modulator in response to an applied bias voltage.
- Calibrate the MZI to control interference between photons according to the applied bias voltage.

References

[1] J. Kim, Z. Croft, D. Steel, and P.-C. Ku, 'Controlled Phase Gate of Spin Qubits in Two Quantum-Dot Single-Photon Emitters', in 2021 Conference on Lasers and Electro-Optics (CLEO), 2021, pp. 1–2.
[2] Z. Chen, Y. Zhou, J.-T. Shen, P.-C. Ku, and D. Steel, 'Two-photon controlled-phase gates enabled by photonic dimers', Physical Review A, vol. 103, no. 5, p. 052610, 2021.
[3] J. Kim, D. Mastropietro, D. Steel, J.-T. Shen, and P.-C. Ku, 'Proposal for chip-scale generation and verification of photonic dimers', Applied Physics Letters, vol. 119, no. 22, p. 224001, 2021.
[4] J. Kim, Z. Croft, D. G. Steel, and P.-C. Ku, 'Optically Controlled Spin Gate Using GaN Quantum Dots', ACS Photonics, vol. 9, no. 5, pp. 1529–1534, 2022.