

## ABSTRACT

Title of Thesis: INTEGRATION OF CLASSICAL/NONCLASSICAL  
OPTICAL NONLINEARITIES WITH PHOTONIC CIRCUITS

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Recent developments in nanofabrication have opened opportunities for strong light-matter interactions that can enhance optical nonlinearities, both classical and non-classical, for applications such as optical computing, quantum communication, and quantum computing. However, the challenge lies in integrating these optical nonlinearities efficiently and practically with fiber-based and silicon-based photonic circuits on a large scale and at low power. In this thesis, we aimed to achieve this integration of classical and quantum optical nonlinearities with fiber-based and silicon-based photonic circuits.

For classical optical applications, optical bistability is a well-researched nonlinear optical phenomenon that has hysteresis in the output light intensity, resulting from two stable electromagnetic

states. This can be utilized in various applications such as optical switches, memories, and differential amplifiers. However, integrating these applications on a large scale requires low-power optical nonlinearity, fast modulation speeds, and photonic designs with small footprints that are compatible with fiber optics or silicon photonic circuits. Thermo-optic devices are an effective means of producing optical bistability through thermally induced refractive index changes caused by optical absorption. The materials used must have high absorption coefficients and strong thermo-optic effects to realize low-power optical bistability. For this purpose, we choose high-density semiconductor quantum dots as the material platform and engineer nanobeam photonic crystal structures that can efficiently be coupled to an optical fiber while achieving low-power thermo-optical bistability.

For applications that require non-classical nonlinearities such as quantum communication and quantum computing, single photons are promising carriers of quantum information due to their ability to propagate over long distances in optical fibers with extremely low loss. However, the efficient coupling of single photons to optical fibers is crucial for the successful transmission of quantum information. Semiconductor quantum dots that emit around telecom wavelengths have emerged as a popular choice for single photon sources due to their ability to produce bright and indistinguishable single photons, and travel long distances in fiber optics. Here, we present our advances in integrating telecom wavelength single photons from semiconductor quantum dots to optical fibers to realize efficient fiber-integrated on-demand single photon sources at telecom wavelengths.

Finally, using the same methodology, we demonstrate the integration of these quantum dots with CMOS foundry-made silicon photonic circuits. The foundry chip is designed to individually tune quantum dots using the quantum confined stark shift with localized electric fields at different sections of the chip. This feature could potentially enable the tuning of multiple quantum emitters for large-scale integration of single photon sources for on-chip quantum information processing.

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CIRCUITS

by

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Thesis submitted to the Faculty of the Graduate School of the  
University of Maryland, College Park, in partial fulfillment  
of the requirements for the degree of  
Doctor of Philosophy  
2023

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## Acknowledgments

I want to first thank my advisor, Professor Edo Waks, for his guidance and generous support of my research through the past 6-7 years at the University of Maryland. While he gave us enough freedom to carry out research and supported it with full strength, we could always get his opinion, suggestions, and help when we had problems. He made it possible for us to try new ideas freely and bravely. Through those weekly meetings where we discussed exciting new ideas, I learned the basic picture of this field and also his philosophy of tackling and handling problems. The longer I work with him, the more knowledge I realize he has.

I am grateful that my dissertation committee members, Professor Goldhar, Professor Murphy, Professor Gong, and Professor Rolston, were willing to take the time to review my thesis and supervise my defense. Professor Gong and Professor Murphy also served on my proposal committee.

I am also thankful for our research scientist Dr. Chang-min Lee and group member Sam Harper. We spent almost five years working closely on similar projects. Dr. Chang-min Lee's guidance and efforts were a massive help in the realization of many of our projects. I also thank all of the other group members I have worked with over the years.

I also want to thank our collaborators at AIM Photonics and MIT, Prof. Dirk Englund, Dr. Carlos Errando-Herranz, Dr. Mike Fanto, and Hugo Larocque for their help in realizing integration with foundry-made silicon photonic circuits. Joint meetings with them were always productive and insightful.

Lastly, I thank my family for their love and support.

# Table of Contents

|                                                                                                                |    |
|----------------------------------------------------------------------------------------------------------------|----|
| Acknowledgments .....                                                                                          | ii |
| List of Figures .....                                                                                          | iv |
| Chapter 1. Introduction .....                                                                                  | 1  |
| 1.1 Overview on integration of optical nonlinearities with fiber-based and silicon photonic circuits.....      | 1  |
| 1.2 Nanobeam Photonic Crystal Structures for Enhancing and Directing Optical Nonlinearities .....              | 4  |
| 1.3 Hybrid Integration Techniques for The Nanobeam Photonic Structures.....                                    | 6  |
| 1.3 Thesis Outline .....                                                                                       | 9  |
| Chapter 2. Integration of Quantum Dots for Efficient Single Photon Collection into Fiber-Optic Circuitry ..... | 10 |
| 2.1 Introduction .....                                                                                         | 10 |
| 2.2 Integration with fiber-optics with taper-to-taper adiabatic coupling .....                                 | 12 |
| 2.3 Integration with fiber-optics with edge-coupling using adiabatic out-couplers .....                        | 20 |
| 2.4 Surface Passivation and Smoothing of InP Nanobeam Cavities.....                                            | 25 |
| 2.5 Conclusion.....                                                                                            | 30 |
| Chapter 3. Integration of Quantum Dots for Tunable Single Photon Sources in Silicon Photonic Circuits .....    | 32 |
| 3.1 Introduction .....                                                                                         | 32 |
| 3.2 Hybrid-Integration of Telecom Quantum Dots with photonic integrated chips with Adiabatic Coupling ...      | 34 |
| 3.3 Tunability of Quantum Dots inside the integrated nanobeams .....                                           | 38 |
| 3.4 Conclusion.....                                                                                            | 38 |
| Chapter 4. Low Power Optical Bistability Quantum Dots-Coupled to Nanobeam Cavity .....                         | 40 |
| 4.1 Introduction .....                                                                                         | 40 |
| 4.2 Theory of Thermo-Optical Bistability.....                                                                  | 41 |
| 4.3 High Density Quantum Dots for Thermo-optical Bistability .....                                             | 44 |
| 4.4 Device Structure, Simulations and Hybrid Fabrication.....                                                  | 46 |
| 4.5 Micro-photoluminescence Measurements and Cavity Characterization .....                                     | 50 |
| 4.6 Input-Output Measurements on Cavity Reflectivity, and Thermo-optical Bistability .....                     | 52 |
| 4.7 Comparison with Nanobeam Cavities without Quantum Dots .....                                               | 55 |
| 4.8 Conclusion.....                                                                                            | 57 |
| Chapter 5. Outlook and Future Directions.....                                                                  | 58 |
| Appendices .....                                                                                               | 60 |
| Appendix A. Experimental Setups for single photon collection.....                                              | 60 |
| Bibliography.....                                                                                              | 61 |

## List of Figures

|                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                               |    |
|-----------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------|----|
| Figure 1. (a) A schematic for nanobeam photonic crystal mirror with a linear taper. (b) A schematic for the nanobeam photonic crystal cavity with a linear taper. ....                                                                                                                                                                                                                                                                                                                                                                        | 5  |
| Figure 2. An illustration of the pick-and-place process with a tungsten microprobe in an SEM/FIB machine. ....                                                                                                                                                                                                                                                                                                                                                                                                                                | 7  |
| Figure 3. An illustration of the pick-and-place process with transfer-printing using a PDMS stamp. ....                                                                                                                                                                                                                                                                                                                                                                                                                                       | 8  |
| Figure 4. (a) Top view schematic for the proposed method. Quantum dots are randomly distributed over the entire waveguide. (b) Side view schematic for the proposed method. Quantum dots are at the center of the nanobeam height (c) FDTD simulation result for the electric field profile from a dipole source in the InP nanobeam that is adiabatically coupled into fiber taper. Brightness for coupling into fiber taper is calculated to be 0.88 for the ideal quantum dot position at the center width of the nanobeam waveguide. .... | 12 |
| Figure 5. SEM images of the fabrication results. (a) SEM image of the fiber taper after dynamic chemical etch procedure. (b) SEM image of an InP nanobeam that contains quantum dots. (c) SEM image of pick-and-place procedure during picking up an InP nanobeam. (d) SEM image of the nanobeam-fiber taper construct after transferring the nanobeam on top of the fiber taper. ....                                                                                                                                                        | 14 |
| Figure 6. Photoluminescence measurement results on InGaAs detectors with above-band pumping of quantum dots with 780 nm CW laser. (a) Entire spectrum with a pump power of 3 $\mu$ W, and 5 seconds integration time. (b) The magnified spectrum of (a) shows the selected quantum dot with a pump power of 2.5 $\mu$ W and 1 second integration time. ....                                                                                                                                                                                   | 17 |
| Figure 7. Second-order auto-correlation measurement results from the quantum dot emission selected in Figure 6 under 780 nm pulsed laser with a repetition rate of 76 MHz. (a) Pump power dependence of single photon count rates in superconducting nanowire single photon detectors. (b) and (c) Second-order auto-correlation results for a pump power of (b) 250 nW and (c) 1.2 $\mu$ W. ....                                                                                                                                             | 18 |
| Figure 8. (a) Schematic for the method of efficient coupling from the nanobeam to objective lens and the optical fiber. (b) Far-field mode profile from nanobeam taper using FDTD simulations. White dashed line represents numerical aperture of objective lens. (c) SEM image of the fabricated nanobeam arrays. Each nanobeam waveguide has a photonic crystal mirror in one end and tapered out-coupler on the other end. ....                                                                                                            | 21 |

Figure 9. Photoluminescence and second-order auto-correlation measurements from the sample. (a) Photoluminescence spectrum from the nanobeam using above-band excitation with 780 nm pulsed laser. Inset is second-order auto-correlation measurement for the selected bright peak at 2  $\mu$ W. (b) Pump power dependence of count rates and  $g_{20}$  at superconducting nanowire single photon detectors. Black dots are  $g_{20}$  values at each pump power. Red circles,  $I_{det}$ , are detected count rates and blue ones,  $I_{corr}$  are corrected ones with  $g_{20}$ . Blue line is the curve fitted to the corrected count rates with parameters  $I_{max} = 1.65 \pm 0.05$  Mcps and  $P_{sat} = 0.91$   $\mu$ W 24

Figure 10. (a) A schematic for a one-sided nanobeam photonic crystal cavity. The cavity consists of one perfectly reflecting mirror segment at the left with  $NL$  number of mirror holes, one partially reflecting mirror segment at the right with  $NR$  number of mirror holes, and a cavity region where periods and holes are linearly tapered. (b) Proposed measurement scheme for edge coupling with lensed fiber.....26

Figure 11. (a) SEM image of the fabricated nanobeam photonic crystal cavities with a tapered end. (b) Optical microscope image of a lensed fiber probing the nanobeam cavities that are transfer-printed at the edge of a silicon piece. ....28

Figure 12. Measured Quality Factor from Nanobeam Cavities with/without Surface Passivation (SP) and 2nm ALD. NR stands for the number of mirror holes on the right side of the cavity where the cavity is coupled to the waveguide. (a) Average quality factor over approximately 10 nanobeam cavities with respect to number of holes in the right side of the cavity. (b) Average deviation for cavity resonance over approximately 10 nanobeam cavities with respect to the number of holes in the right side of the cavity.....29

Figure 13 (a) A schematic for the top view of the proposed method. (b) Cross-sectional view of the proposed method. (c) Electric field mode profile from FDTD simulation result for coupling between InP nanobeam taper to Silicon Waveguide taper.....34

Figure 14. (a) Optical microscope image of the PIC. (b) SEM images for the fabricated InP nanobeams with small and large pads.....35

Figure 15 (a) SEM image of an InP nanobeam transferred on a quantum socket using a tungsten probe and pick-and-place method. (b) Optical microscope image of InP nanobeams transferred on quantum sockets using a PDMS

|                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                           |    |
|-------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------|----|
| stamp and transfer-printing method (c) Photoluminescence spectrum from quantum dots in the third single nanobeam in (b). (d) Second-order autocorrelation measurement for the selected bright dot emission in (c). ....                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                   | 36 |
| Figure 16. Tunability results from applied voltage over top and bottom electrodes. (a) Wavelength shift with respect to increasing and decreasing applied voltage. (a) Change in the linewidth of the quantum dot emission with respect to the applied voltage. (c) Count rates with respect to the applied voltage. ....                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                 | 38 |
| Figure 17. A schematic of a leaky optical cavity with thermo-optical absorber .....                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                       | 41 |
| Figure 18. Numerical results from the simple theory of thermo-optical bistability. (a) Cavity reflectivity with respect to detuning ( $\Delta\omega$ ) for increasing input power $bin2$ . (b) Input-output power relation for different detuning ( $\Delta\omega$ ). Hysteresis observed after satisfying the condition $\Delta\omega < -3\Gamma/2$ . (c) Input-output power relation for different heat conductivity (K). Increasing bistability threshold is observed with increasing heat conductivity, since $ab2$ is linearly dependent on K. ....                                                                                                                                                                                                                                                                                  | 43 |
| Figure 19. Quantum Dots wafer information. (a) Layered structure of quantum dot wafer. (b) Photoluminescence emission from bulk quantum dot wafer under above-band excitation with 780nm CW laser .....                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                   | 45 |
| Figure 20. (a) The tapered nanobeam photonic crystal cavity design with lattice parameter $a = 365$ nm, hole radius $r = 0.29 a$ and $r1..6 = 0.29 a1..6$ . Number of holes in the mirror segments on right and left side are $NR = 4$ and $NL = 9$ respectively. The cavity region is realized by tapering and shifting 12 holes located between two mirror segments. The width of the nanobeam waveguide is $w = 480$ nm and width of taper end is $b = 150$ nm. Nanobeam width is adiabatically reduced from 480nm to 150 nm at the end of the 8 $\mu$ m-long taper. Thickness of the nanobeam is 200 nm. (b) The far field mode profile from the nanobeam taper and fundamental mode profile of the cavity is shown here. White dashed line in far field profile corresponds to numerical aperture of 0.7 of the objective lens. .... | 46 |
| Figure 21. (a) SEM image of a nanobeam array, attached to a pad that is suspended with support bridges. (b) SEM image of the transferred nanobeam array, suspended at the edge of a silicon carrier chip. (c) A schematic of the measurement setup for the transferred nanobeam array. ....                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                               | 48 |

|                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                              |    |
|--------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------|----|
| Figure 22. (a) The reflected light from the nanobeam using a broadband input laser. The cavity-dip is centered around 1284.5 nm. (b) Photoluminescence measurement using above-band 780 nm CW pump laser excitation of the nanobeam photonic crystal cavity. The cavity emission is fit to a Lorentzian curve to find the quality factor of 2830. (c) Photoluminescence measurement using above-band 780 nm CW pump laser excitation of the bare QD sample. Red line shows the position of cavity resonance on quantum dots distribution. ....                                                                                                                                                               | 50 |
| Figure 23. The reflected intensity from the cavity as the incident continuous wave laser is scanned across the cavity resonance at different power levels. ....                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                              | 52 |
| Figure 24. The cavity reflectivity for input power with different detuning $\delta$ of wavelength of CW laser from wavelength of the cavity resonance. $\delta = \lambda_L - \lambda_c$ , where $\lambda_L$ is the wavelength of incident light and $\lambda_c$ is the wavelength of the cavity resonance. The red and blue data points represent increasing and decreasing incident power, respectively. (a) $\delta = 0$ nm. CW laser is resonant with the cavity. (b) - (f) $\delta$ is 0.1 nm - 0.8nm respectively. CW laser is red detuned from the cavity resonance. Input power is measured before the objective lens and adjusted according to coupling efficiency into the nanobeam waveguide. .... | 54 |
| Figure 25. Input and output optical power from the nanobeam without quantum dots for different detuning $\delta$ . The red and blue data points represent increasing and decreasing incident power, respectively. The quality factor of the cavity is around 3300. ....                                                                                                                                                                                                                                                                                                                                                                                                                                      | 56 |
| Figure 26. Experimental setups used for measurements in (a) Chapter 2.2 and (b) Chapter 2.3 .....                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                            | 60 |

# Chapter 1. Introduction

## 1.1 Overview on integration of optical nonlinearities with fiber-based and silicon photonic circuits

Optical nonlinearities are a crucial component for a wide range of photonic applications, including optical communications, sensing, and quantum information processing [1]. Nonlinear optical effects are responsible for enabling many key functionalities in these systems, such as wavelength conversion [2], frequency mixing [3], phase modulation [4], optical activation functions [5] and quantum emitters [6]. While fibers and silicon photonics are both important platforms for the photonics, they have inherent limitations in terms of their nonlinear optical properties [7-8]. For example, silica fibers have a relatively low nonlinear coefficient, which limits their efficiency for certain nonlinear processes [7]. On the other hand, silicon photonics suffers from a lack of strong intrinsic nonlinearities, which makes it challenging to implement certain nonlinear effects directly in the material [8]. By integrating other material platforms with fibers and silicon photonics, it is possible to leverage the unique nonlinear optical properties of these materials to overcome the limitations of each platform. For example, materials such as lithium niobate [9], silicon nitride [10], and gallium arsenide [11] have much stronger nonlinearities than silica fibers or silicon and can be integrated with these platforms to enhance their nonlinear functionality.

The integration of classical optical nonlinearities with fiber optics is of paramount importance due to the ever-growing demand for higher data rates, extended reach, and enhanced functionalities in modern communication networks, as well as the need for advanced sensing and imaging applications [12]. Fiber optics, as a low-loss, high-bandwidth medium, inherently supports these nonlinearities, enabling a wide range of applications such as optical switching, signal amplification, wavelength conversion, and optical signal processing, all within the optical domain [12]. By leveraging the

advantages of nonlinear phenomena in conjunction with the exceptional transmission properties of optical fibers, it becomes possible to develop more efficient, compact, and robust systems, while reducing energy consumption and latency associated with electronic conversions. Furthermore, the integration of nonlinear optical effects with fiber optics facilitates the realization of novel techniques such as supercontinuum generation [13], soliton transmission [14], and nonlinear microscopy [15], opening new avenues for innovation in various scientific and industrial fields. Such applications are essential for driving the development of cutting-edge technologies and meeting the challenges of next-generation communication, sensing, and imaging systems [1].

The integration of classical optical nonlinearities with silicon photonics is crucial for the advancement of on-chip optical devices and systems, offering new opportunities for efficient, high-speed, and compact photonic integrated circuits (PICs) [16]. Silicon, a widely available and well-understood material, boasts compatibility with complementary metal-oxide-semiconductor (CMOS) fabrication processes, which makes it a promising platform for large-scale, cost-effective production of optical devices [16]. By incorporating optical nonlinearities into silicon photonics, it becomes possible to expand the range of functionalities offered by PICs, such as all-optical signal processing, wavelength conversion, and optical switching [16]. This, in turn, leads to improved performance, energy efficiency, and reduced latency for on-chip optical interconnects and computing applications. Furthermore, the combination of nonlinear optical effects and silicon photonics opens up new possibilities in sensing, imaging, and quantum information processing, fostering innovation across multiple scientific and industrial domains [16-17]. Realizing classical optical nonlinearities in silicon photonics is vital for pushing the boundaries of photonic technologies and enabling the development of sophisticated, miniaturized, and energy-efficient optical systems.

Single photons, as the fundamental units of light, serve as ideal carriers of quantum information due to their low-noise properties, inherent immunity to eavesdropping, and capacity for secure communication [17-18]. The integration of single-photon sources with fiber optics is essential for the advancement of quantum communication, quantum computing, and quantum sensing technologies, as it enables the efficient, robust, and long-distance transmission of quantum information [17-18]. By incorporating single-photon sources into fiber optics, it becomes feasible to develop practical and user-friendly quantum systems, overcoming the limitations of bulky, lab-based experimental setups [19-20]. This integration facilitates the realization of quantum key distribution, quantum repeaters, and quantum networks, which rely on the precise transmission of single photons through single-mode fibers [19]. Furthermore, fiber-coupled single-photon sources offer enhanced long-term stability, scalability, and compatibility with existing telecommunication infrastructure, making them well-suited for real-world applications [19].

Silicon photonics is a mature platform known for its compatibility with complementary metal-oxide-semiconductor (CMOS) fabrication processes, high component density, and low-loss performance, making it an attractive choice for on-chip quantum photonic systems. Realizing single-photon sources within silicon photonics paves the way for integrated quantum circuits capable of performing complex quantum operations, such as quantum simulations, quantum error correction, and quantum machine learning [20]. Additionally, this integration facilitates the convergence of classical and quantum photonic technologies, offering a versatile platform for hybrid systems that can leverage the strengths of both domains [20]. The incorporation of single-photon sources in silicon photonics also enhances the compatibility of quantum devices with existing telecommunications infrastructure, accelerating the deployment of quantum technologies in real-world applications.

In this thesis, we demonstrate our advances in integrating classical and nonclassical optical nonlinearities derived from semiconductor quantum dots (QDs) with fiber optics and silicon photonics. Semiconductor quantum dots offer a promising platform for realizing optical nonlinearities, owing to their unique electronic and optical properties that arise from their quantum confinement effects [21-22]. These nanoscale structures provide discrete energy levels that can be tuned via size and composition, enabling precise control of their optical response. The inherent strong light-matter interaction within QDs leads to significant nonlinear optical effects, such as four-wave mixing, parametric down-conversion, and quantum interference [21-22]. This allows for the generation of non-classical light states, including single and entangled photons, which are crucial for various quantum information processing tasks [21-22]. Additionally, the nonlinear properties of QDs can be further enhanced by embedding them in photonic structures, such as microcavities and waveguides, improving their efficiency and interaction with external fields [22]. QDs also exhibit ultrafast response times, making them suitable for high-speed, all-optical signal processing and switching applications [22]. Finally, advanced hybrid fabrication techniques of III-V materials make QD-based optical nonlinearities ideal candidates for integration with fiber-based and silicon-based photonic circuits [21-22].

## 1.2 Nanobeam Photonic Crystal Structures for Enhancing and Directing Optical Nonlinearities

Nanobeam photonic structures are state-of-the-art nano-engineered platforms that have garnered significant attention in recent years due to their potential for revolutionizing a wide range of applications, from telecommunications to quantum computing [23-24]. These intricate structures are formed by patterning dielectric materials with periodic arrays of nanoscale features, manipulating light on the sub-wavelength scale to create an array of optical properties. The inherent versatility of nanobeam photonic

structures allows for the precise engineering of light-matter interactions, fostering the development of compact and energy-efficient devices such as lasers, sensors, and optical switches [23-24]. Moreover, by leveraging advanced fabrication techniques and material advancements, researchers continue to explore novel avenues for harnessing the unique properties of these structures, ultimately driving breakthroughs in areas such as quantum information processing, integrated photonics, and nanoscale optomechanics [23-24].

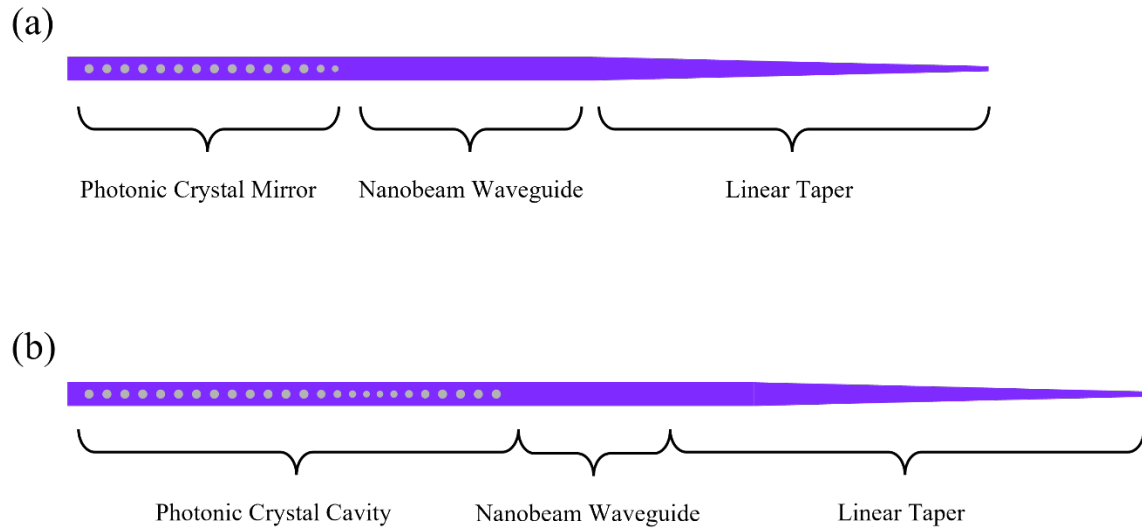


Figure 1. (a) A schematic for nanobeam photonic crystal mirror with a linear taper. (b) A schematic for the nanobeam photonic crystal cavity with a linear taper.

Figure 1 illustrates a schematic for nanobeam photonic crystal structures used in this thesis to enhance and direct optical nonlinearities in the nanobeam. Figure 1 (a) shows the nanobeam photonic crystal mirror design which consists of a one-dimensional photonic crystal mirror region, a nanobeam waveguide region, and a linear taper region. The primary use of this design is to predominantly direct light generated inside the nanobeam towards linear taper. Linear taper is then used for adiabatically coupling light into fiber optics or silicon waveguides. Figure 1 (b) shows the nanobeam photonic crystal cavity design which consists of a one-sided photonic crystal cavity region, a nanobeam waveguide

region, and a linear taper region. The primary use of this design is to enhance the light-matter interaction and optical nonlinearities inside the photonic crystal cavity and then couple it to the nanobeam waveguide. Linear taper is again used for adiabatically coupling light into fiber optics or silicon waveguides. By carefully engineering the linear taper, these designs offer a wide range of options for manipulating and enhancing optical nonlinearities within the nanobeam, and for coupling it to a variety of photonic circuits with versatility.

### 1.3 Hybrid Integration Techniques for The Nanobeam Photonic Structures

To realize the potential of the nanobeam photonic structures from different material platforms in other photonic circuits, we need hybrid integration techniques that can help us to fabricate or place these devices in a manner where we can use linear tapers to couple into other photonic circuits. Hybrid integration methods, including epitaxial heterogrowth, wafer bonding, and pick-and-place offer a promising solution for such a task, which may not be feasible through a single fabrication process [25]. Among them, epitaxial heterogrowth, and wafer bonding offer precise positioning for hybrid integration, however, they are still quite challenging and require too much expertise to engineer the entire fabrication process [25]. Moreover, while they are good for integrating with silicon photonics, they do not offer a solution to use our design to couple into fiber optics. For these purposes, we choose the two main pick-and-place methods that are pick-and-place with tungsten probe and transfer-printing as our main techniques in hybrid fabrication and positioning of the nanobeam photonic structures.

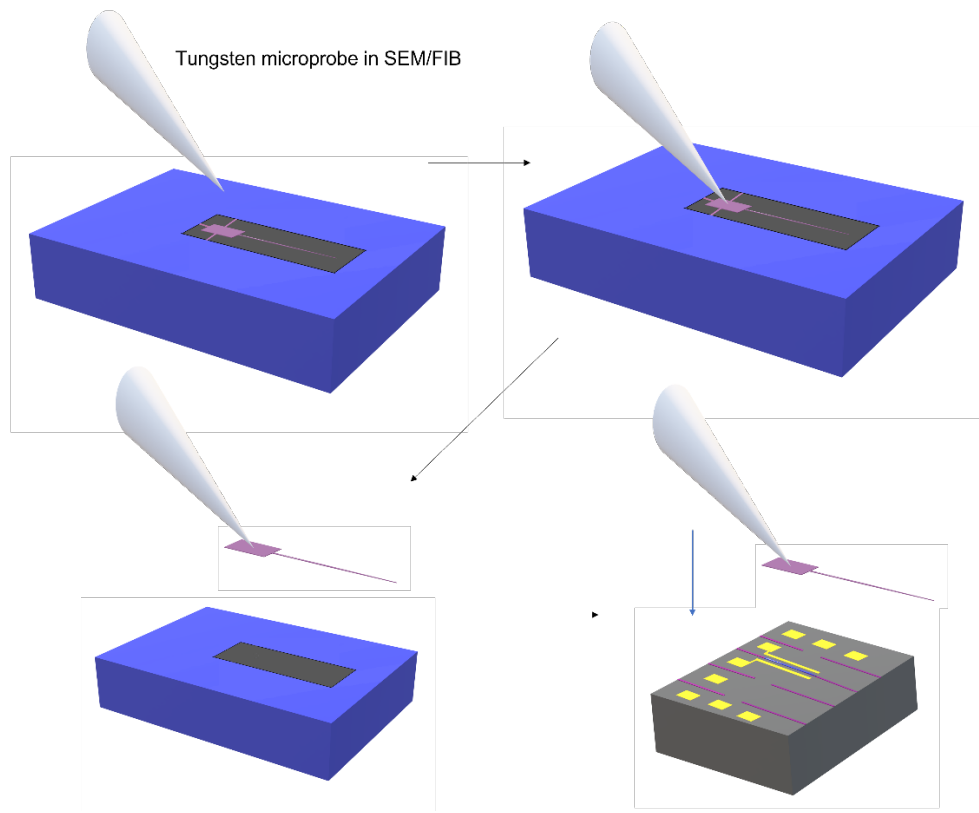


Figure 2. An illustration of the pick-and-place process with a tungsten microprobe in an SEM/FIB machine.

Figure 2 shows an illustration of the pick-and-place process with the tungsten microprobe used in this thesis. We use a tungsten microprobe installed in a focused ion beam system/scanning electron microscope, FIB/SEM, system. While monitoring the process with SEM, we first move the microprobe and gently touch the tip of the microprobe to the handlers of a suspended nanobeams from the chosen material platform. In our case, the material platform is semiconductor quantum dots which are patterned with electron beam lithography and nanobeam handlers are rectangular pads. After touching the nanobeam handle, we use the FIB machine to etch-cut tethers attaching the nanobeam to the sample substrate. Once, the nanobeam is free from the substrate and we can move the probe attached to the nanobeam using the motorized control of the microprobe. Finally, we moved it to on top of the other

photonic circuits or fiber optics to gently place it down on the desired position while monitoring with the SEM machine.

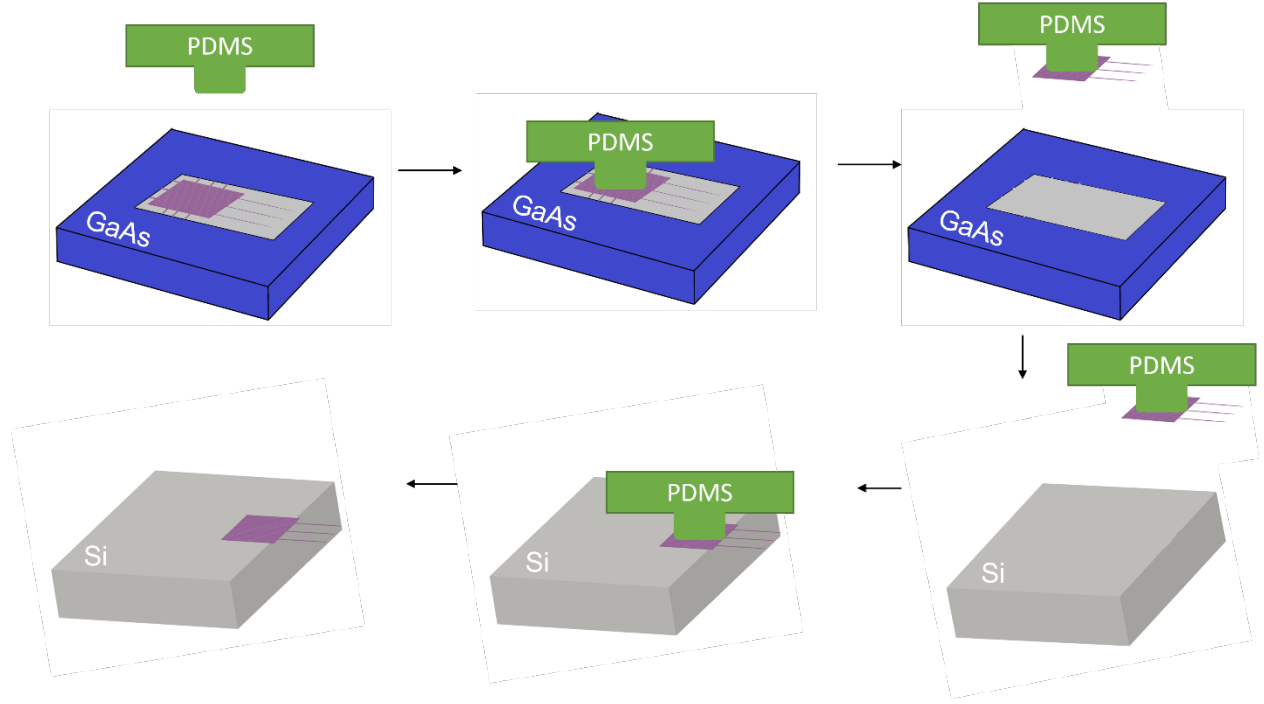


Figure 3. An illustration of the pick-and-place process with transfer-printing using a PDMS stamp.

Figure 3 shows an illustration of the pick-and-place process with transfer-printing using a transparent polydimethylsiloxane (PDMS) stamp. The process is monitored with a zoom-lens optical microscope system from the top through a transparent PDMS stamp. Different from the previous method, we use a PDMS stamp to attach to the nanobeam rectangular pads. Since we do not have a FIB process, we force-break the thin tethers attaching the nanobeam to the substrate by slightly moving the PDMS stamp after the attachment. Then, similarly, to the previous process, we move the stamp-nanobeam to the desired photonic circuit or carrier sample and gently place it. PDMS stamp is fabricated using optical lithography and can also be commercially purchased. There are two advantages of using a PDMS stamp instead of a microprobe. The first advantage is the scalability of the number of nanobeams transferred in each pick-and-place process. Since PDMS stamps can be at custom size, it is usually much easier to pick-

up large structures. This feature helps to transfer an array of nanobeam structures attached to the same large pad in one process. Moreover, instead of a single PDMS stamp, a matrix of PDMS stamps can be patterned with optical lithography. This could potentially help large-scale integration projects that need different photonic structures transferred in one process step. The disadvantage of using this method comes with the precision and accuracy of positioning of nanobeams on the photonic circuits. Since the monitoring is done with an optical microscope, it is often difficult to see exact borders of nanobeam in high resolution. Additionally, since we need to print-it-down to the photonic circuits, it would be difficult to use this method to transfer nanobeams on top of photonic structures that require gentle handling such as fiber tapers or suspended membranes on silicon photonics.

### 1.3 Thesis Outline

In the following chapter, we will describe how we have integrated semiconductor quantum dots embedded into the nanobeam photonic structures to generate fiber optics and silicon photonics coupled with classical and quantum optical nonlinearities. Chapter 2 will be about integrating InAs/InP quantum dots that emit single photons in telecom O-band into fiber-optics to realize fiber-coupled bright single photon sources. Chapter 3 will be about integrating the same quantum dots with foundry-made silicon photonic circuits to realize on-chip tunable single photon sources. Then, chapter 4 will be about integrating high density InAs/GaAs quantum dots with fiber optics to realize fiber-coupled low power thermo-optical bistability. In Chapter 5, we will give a conclusion to this dissertation and discuss future experiments. Finally, in the appendixes, we will show the measurement setups used through Chapter 2.

## Chapter 2. Integration of Quantum Dots for Efficient Single Photon Collection into Fiber-Optic Circuitry

### 2.1 Introduction

Quantum information science has the potential to revolutionize the way we communicate and process information. One of the fundamental challenges in this field is the ability to transmit and process quantum information over long distances. Single photons have emerged as promising carriers of quantum information due to their ability to propagate over long distances in optical fibers with the extremely low loss [18-20]. However, efficient coupling of single photons to optical fibers is crucial for the successful transmission of quantum information to the receiver or detector in applications such as quantum communication and photonic quantum computing [19].

Most single photon sources emit into free space, and coupling these sources to optical fibers requires bulky optics that require precise optical alignment and can be lossy due to imperfect mode-matching [26-32]. Thus, developing efficient coupling schemes between single photon sources and optical fibers is critical to improving the efficiency of single photon sources for practical applications.

Semiconductor quantum dots have emerged as a popular choice for single photon sources due to their ability to produce bright and indistinguishable single photons [21]. Recent studies have also reported quantum dots that emit at telecom wavelengths, where photon transmission loss in optical fibers is minimized [21]. However, efficient coupling of these single photon sources with optical fibers is still necessary for constructing long-distance quantum networks.

Various photonic nanostructures have been explored to enhance the efficiency of single photon sources, including nanowires, planar photonic crystal waveguides, and cavities [33-35]. These structures have different advantages in terms of collecting photons from the emitter, such as coupling the single photons to the nanostructure's optical mode or enhancing the directional far-field emission. However, to achieve single photon sources sufficient for long-distance quantum networks, the out-coupling efficiency of telecom-wavelength single photons into an objective lens and subsequent optical fiber needs improvement. To that aim, fiber-coupled single photon sources have been reported using semiconductor quantum dots or nitrogen-vacancy centers in diamond [19,36-38]. However, these systems require constant realignment and are sensitive to vibrations and temperature fluctuations because the fiber taper and the photonic waveguide move independently. Other studies have directly attached single photon emitters to a fiber taper or a cleaved facet of the fiber, but these sources lack engineered structures for effective mode-matching and emit at wavelengths outside the telecom bandwidth [39-40]. Therefore, developing new integrated quantum photonic circuits that can efficiently couple single photons with optical fibers could lead to significant improvements in the efficiency of single photon sources for practical applications.

In this chapter, we will show the advances we have made toward integrating telecom wavelength single photons from semiconductor quantum-dots with optical fibers to realize efficient fiber-integrated on-demand single photon sources at telecom wavelengths [96, 97]. We will start by introducing semiconductor quantum dots used as a single photon source. Then, we will explain two main mechanisms we employed for efficiently coupling single photons from quantum dots into an optical fiber. Then, we will demonstrate the measurement results for experimental coupling efficiency and comparisons with other quantum-dot based sources.

## 2.2 Integration with fiber-optics with taper-to-taper adiabatic coupling

In the first method to efficiently integrate quantum dots with fiber optics, we incorporated them directly onto tapered optical fibers inside a nanobeam taper with a photonic crystal mirror for optimal collection of single photons from individual quantum dots from nanobeam into the fiber taper via adiabatic coupling. Figures 4(a) and 4(b) illustrate the fiber-integrated single photon source, which features a 280 nm thick nanobeam waveguide containing InAs/InP quantum dots in the center height, attached to a tapered fiber. Although the quantum dots are randomly distributed across the entire nanobeam when viewed from above, an optimal position is highlighted in Figure 4 using a green mark. The nanobeam includes a photonic crystal mirror made up of an array of etched holes on one end, which directs the quantum dot emission toward the optical fiber. To seamlessly transfer the nanobeam-guided single photons to the underlying fiber taper, we gradually taper one end of the nanobeam to ensure adiabatic transfer. The tapered fiber then transforms the optical mode of the photon into the mode of the bare optical fiber.

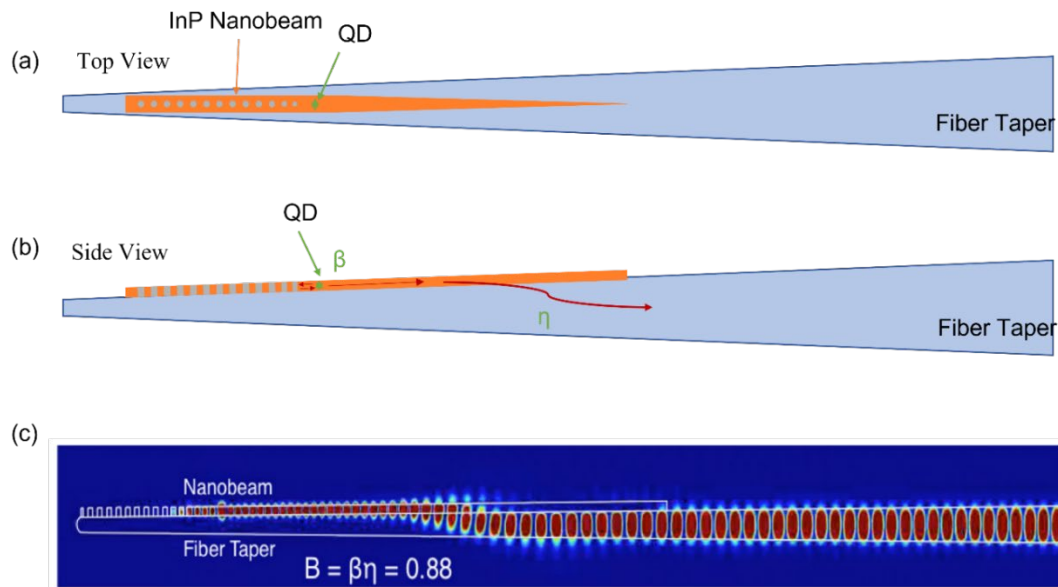


Figure 4. (a) Top view schematic for the proposed method. Quantum dots are randomly distributed over the entire waveguide. (b) Side view schematic for the proposed method. Quantum dots are at the center of the nanobeam

height. (c) FDTD simulation result for the electric field profile from a dipole source in the InP nanobeam that is adiabatically coupled into fiber taper. Brightness for coupling into fiber taper is calculated to be 0.88 for the ideal quantum dot position at the center width of the nanobeam waveguide.

Figure 4 (c) shows the electric field intensity map from finite difference time domain (FDTD) simulations for the InP nanobeam and fiber taper construct. Brightness into the fiber taper,  $B$ , is calculated from the total power transmitted into the fiber taper from a dipole source in the middle of the nanobeam waveguide.  $\beta$  is the single mode coupling efficiency to the nanobeam waveguide mode and  $\eta$  is the adiabatic coupling efficiency between the nanobeam taper and fiber taper. Nanobeam mirror reflectivity is simulated to be close to unity. Therefore, in simulations for the InP nanobeam and fiber taper, brightness depends mostly on  $\beta$  and  $\eta$  as  $B = \beta \eta$ . However, in actual experiments with quantum dots, it also largely depends on the quantum efficiency of quantum dots emitting a single photon. Using FDTD simulations, we have optimized the parameters for the nanobeam taper, and the fiber taper to reach the maximal value for brightness while making sure that it is a feasible design for fabrications. After these considerations, the device has a nanobeam waveguide width of 400 nm, a 13-hole photonic crystal Bragg mirror, a 10  $\mu\text{m}$  waveguide region, and a 15  $\mu\text{m}$  taper that ends with a 50 nm tip. Nanobeam height is the same as the membrane thickness from the wafer, which is 280 nm. Fiber taper, on the other hand, has a taper angle of  $1^\circ$ , and approximately 100 nm tip diameter. Assuming close to unity quantum efficiency, and mirror reflection, these parameters produce a 0.88 brightness.

To realize such a device, we begin our fabrication with fiber tapers. We used a single mode bare optical fiber, and a dynamical chemical etch procedure to realize fiber tapers with desired parameters [41]. During this procedure, we removed the coating from one end of an optical fiber and immersed it into a 50% hydrofluoric acid (HF) solution for about 45 minutes. As the fiber's tip gradually dissolved, we utilized a motorized stage to slowly extract the fiber from the solution. By adjusting the HF

concentration and pull-out velocity, we were able to regulate the taper angle. Consequently, we created fiber tapers with a taper angle of  $1^\circ$ , and a tip diameter of approximately 100 nm. Figure 5 (a) shows a scanning electron microscope (SEM) image of the fiber taper.

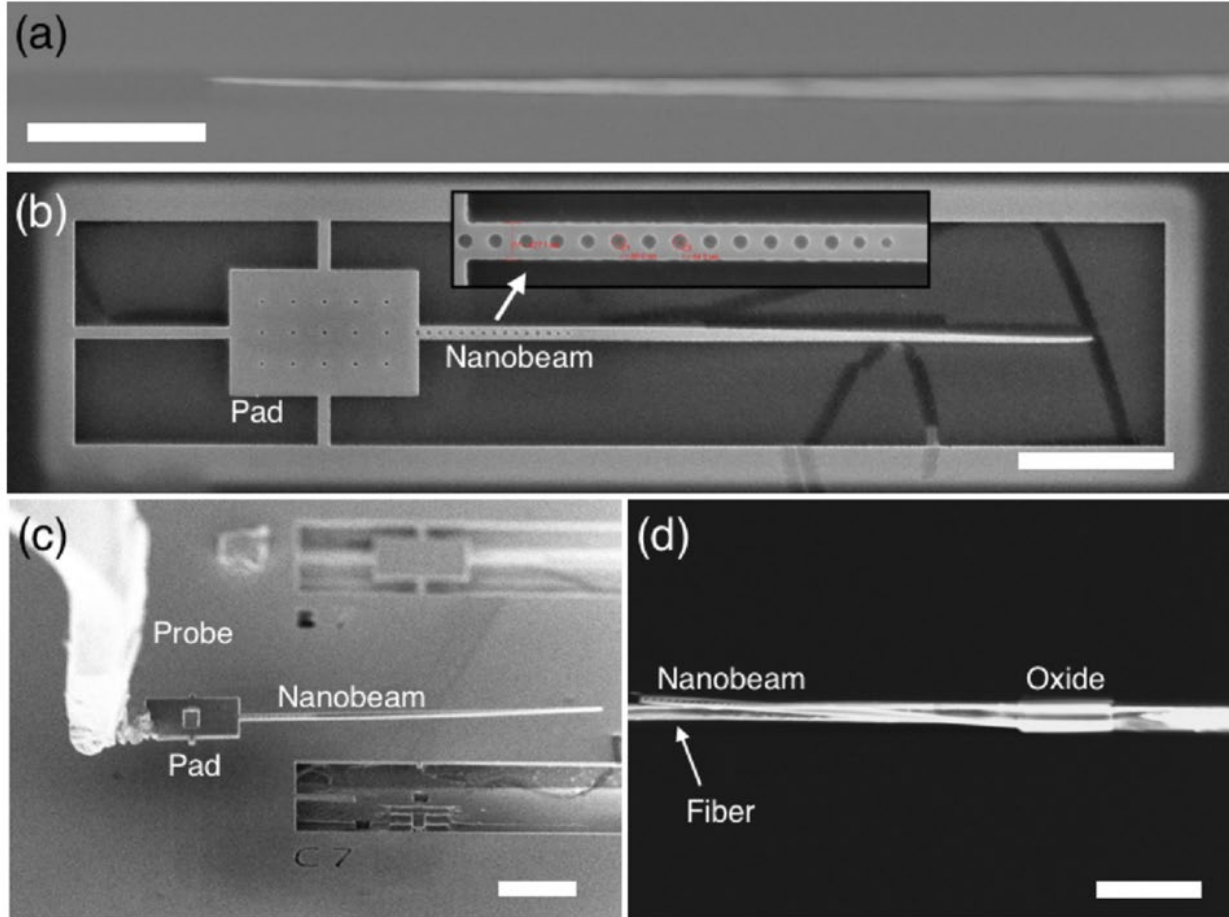


Figure 5. SEM images of the fabrication results. (a) SEM image of the fiber taper after dynamic chemical etch procedure. (b) SEM image of an InP nanobeam that contains quantum dots. (c) SEM image of pick-and-place procedure during picking up an InP nanobeam. (d) SEM image of the nanobeam-fiber taper construct after transferring the nanobeam on top of the fiber taper.

The next step in the fabrication process was InP nanobeam containing InAs quantum dots. For this purpose, we used the InP wafer that has a 280 nm InP membrane on top of a  $2\text{ }\mu\text{m}$  AlInP sacrificial layer. Since dry-etching of InP requires too high temperatures for soft masks to survive, we have

deposited a 220 nm silicon nitride hard mask using plasma-enhanced chemical vapor deposition. We patterned the silicon nitride hard mask using an electron beam, fluorine-based reactive ion etching. After removing the e-beam resist, we used chlorine-based reactive ion etching to transfer the nanobeam pattern from the hard mask to the InP membrane. Lastly, we removed AlInP sacrificial layer using a selective wet etch to produce suspended nanobeams attached to a rectangular pad as shown in the SEM image in Figure 5 (b). The rectangular pad is added to help during the transfer process from the InP sample to on top of the fiber taper.

To transfer the nanobeam from the InP sample to on top of the fiber taper, we used a tungsten microprobe installed in a focused ion beam system and monitor the process with SEM in the same system as explained in Chapter 1. Firstly, we move the microprobe and gently touch the tip of the microprobe to the edge of the rectangular pad. Normally, this would be enough to provide enough attraction between the microprobe and pad to pick up small structures, however, due to the length of the nanobeam and its taper, it is not enough in our case to remove the nanobeam from the substrate. To better attach nanobeams to the microprobe, we used a focused ion beam and deposited a small amount of silicon dioxide as glue between the microprobe tip and the rectangular pad. After that, we used a focused ion beam to cut the tethers attaching the rectangular pad to the substrate, and moved the probe to pick up the sample. Figure 5 (c) shows the SEM image of a picked-up nanobeam glued to the microprobe tip. Then, using the motorized control of the microprobe, we moved it on top of the fiber taper that is loaded together with the InP sample into the FIB/SEM machine. After gently placing the nanobeam on top of the fiber taper, we deposited a small amount of silicon dioxide at the tip of the nanobeam in order to glue the nanobeam taper to the fiber taper. This is done because we have noticed that nanobeam could move around, and change positions on the fiber taper if we did not properly glue it at the tip of the nanobeam. Then, we

used a short FIB etch on the pad-nanobeam connection to detach the microprobe, and pad from the nanobeam. Figure 5 (d) shows an SEM image of the final nanobeam-fiber taper construct.

To characterize the quantum dot emission from nanobeams into the fiber, we constructed an all-fiber photoluminescence measurement setup as explained in Appendix A. All measurements were conducted within a closed-cycle cryostat, which cooled the sample to 4K. To achieve this, we utilized a helium gas (16 Torr) filled cryostat, attocube attoDry 1000, enabling us to cool the sample without a direct thermal connection to a coldfinger. The quantum dots were stimulated with a Ti:Sapphire laser, which we operated at 780 nm in both continuous-wave and pulsed modes, with a repetition rate of 76 MHz. To measure the spectrum, we utilized a monochromator and InGaAs array detectors to measure the photons. For autocorrelation measurements, we employed a tunable fiber filter to filter out the individual peaks of a selected quantum dot emission and measured the photons using superconducting nanowire single photon detectors.

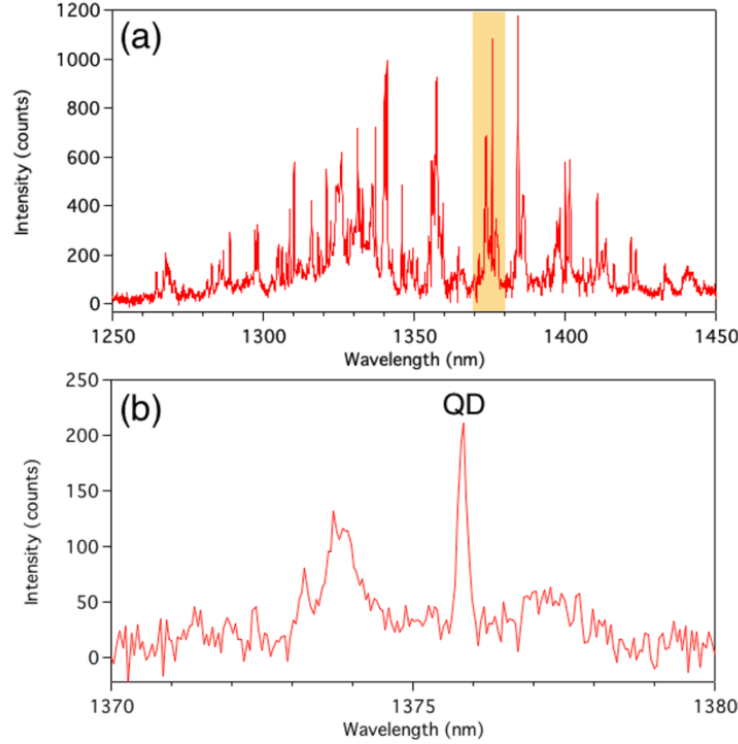


Figure 6. Photoluminescence measurement results on InGaAs detectors with above-band pumping of quantum dots with 780 nm CW laser. (a) Entire spectrum with a pump power of 3  $\mu\text{W}$ , and 5 seconds integration time. (b) The magnified spectrum of (a) shows the selected quantum dot with a pump power of 2.5  $\mu\text{W}$  and 1 second integration time.

Figure 6 shows the photoluminescence measurement results from quantum dots with above-band excitation using a 780 nm CW laser. Excitation is done through the fiber and the emission is collected back from the fiber. Figure 6 (a) shows the entire spectrum of quantum dots emission from the nanobeam with a pump power of 3  $\mu\text{W}$ , and 5 seconds integration time. Figure 6 (b) shows the magnified version of (a) to show the selected quantum dot for further characterization. In this case, we used 2.5  $\mu\text{W}$ , and 1 second integration time.

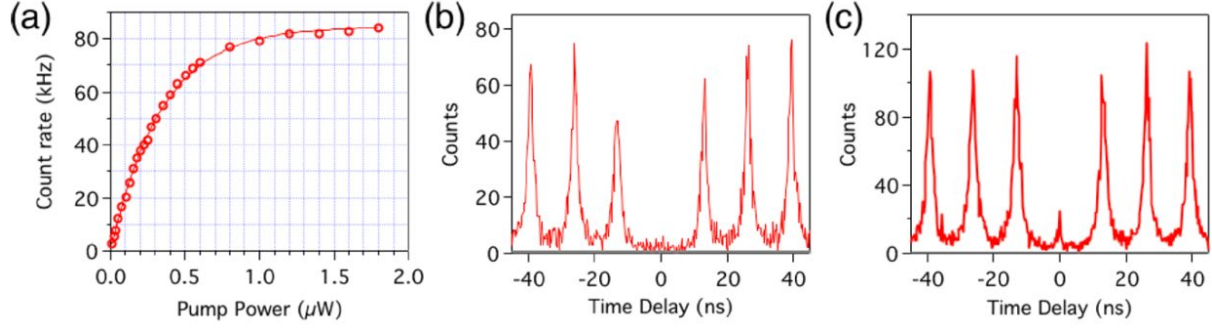


Figure 7. Second-order auto-correlation measurement results from the quantum dot emission selected in Figure 6 under 780 nm pulsed laser with a repetition rate of 76 MHz. (a) Pump power dependence of single photon count rates in superconducting nanowire single photon detectors. (b) and (c) Second-order auto-correlation results for a pump power of (b) 250 nW and (c) 1.2 μW.

To characterize the quantum dot emission selected in Figure 3, we performed second-order auto-correlation measurements using superconductor nanowire single photon detectors under excitation from a 780 nm pulsed laser with a repetition rate of 76 MHz. Figure 7 (a) shows the pump power dependence of the total single photon count rate in the detectors which shows a saturation behavior expected from single quantum dot emission. We fit this data to a saturation equation in the form of  $I(P) = I_0 + I_{\max}(1 - e^{-\frac{P}{P_{\text{sat}}}})$ , where  $I_0$  is the dark count,  $I_{\max}$  is the maximum count rate,  $P_{\text{sat}}$  is the saturation power and  $P$  is the incident pump power. This fit allowed us to calculate  $I_{\max}$  maximum count rate to be 84 kcps (kilo-count per second) under 76MHz pump repetition. Figure 7 (b) and (c) shows the second-order auto-correlation results under 250 nW and 1.2 μW pump power respectively. Here, we used a 50/50 fiber beam splitter to split the collected emission into two paths that go into independent single photon detectors. Coincidence counts between two detectors is obtained using time-correlated single photon counters. Figure 7 (b) and (c) shows the histograms representing this correlation in the form of second order correlation of  $g_2(\tau)$ . To determine  $g_2(0)$ , we standardized the counts at the center over a period of

13.16 ns to the mean coincidence counts of the closest three peaks on either side. We also quantified the background counts created by the detectors' dark count and deducted them from the coincidence counts.

To assess the fiber-coupled brightness of this system, we conducted measurements on the transmissions of all system components, including the fiber vacuum feed-through, fiber filter, couplers, and connectors. We determined the total system detection efficiency, which takes into account the transmissions of each component, to be 7%. Using the measured single photon count rate  $I_{\max}$  of 84 kcps, a setup detection efficiency  $T$  of 7%, a  $g_2(0)$  value of 0.17, and a pump laser repetition rate  $R$  of 76 MHz, we calculated the brightness. We disregarded the additional counts from the multiphoton emission utilizing the  $g_2(0)$  value. The collected single photon at the initial fiber was 1.1 Mcps. Therefore, the brightness of our fiber-integrated single photon source equates to  $B = I/R = 1.4\%$ .

There is a notable inconsistency between the calculated and measured brightness values. To identify the source of the additional loss, we assessed the reflectivity of the fiber-integrated nanobeam utilizing a broadband light source. Our results revealed that the amount of back-reflected light was roughly 1%, indicating an eta of approximately 10%. Hence, we believe that the contact and alignment between the nanobeam and fiber taper are not optimal. We also observed that the nanobeam occasionally detaches from the fiber taper during the cooling process. To monitor this, we observed the broad photoluminescence emitted by the nanobeam during cooling and occasionally detected the sudden vanishing of the signal, indicating that the nanobeam had detached. The detachment of the nanobeam may be due to the distinct thermal expansion coefficients between InP and silicon dioxide. To prevent the nanobeam from detaching, we introduced a silicon dioxide and aluminum oxide layer after the nanobeam transfer, which could cause additional loss.

## 2.3 Integration with fiber-optics with edge-coupling using adiabatic out-couplers

In the second method to efficiently integrate quantum dots with fiber optics, instead of designing nanobeam taper for adiabatic coupling, we have redesigned it to optically mode-match for edge coupling to a single objective lens with a large numerical aperture (NA), and then recouple it onto the fiber. Figure 8 (a) shows the schematic for the InP nanobeam arrays containing InAs quantum dots with a tapered end edge-coupled to an objective lens with NA of 0.66. Nanobeam taper is designed so that single photons from quantum dots are efficiently collected by the objective lens and then coupled into an optical fiber. The other end of the nanobeam has again a photonic crystal mirror to make sure all of the emission is in the direction towards the objective lens. Instead of adiabatic coupling in the previous method, in this method, the tapered-end of the nanobeam spatially expands the optical mode in the nanobeam waveguide so that it can be efficiently collected by objective lens [42]. Another difference in this method is that instead of transferring and working on single nanobeams, we have enlarged the rectangular pads attached to the nanobeam and created arrays of nanobeam in order to test multiple devices in one experimental cycle.

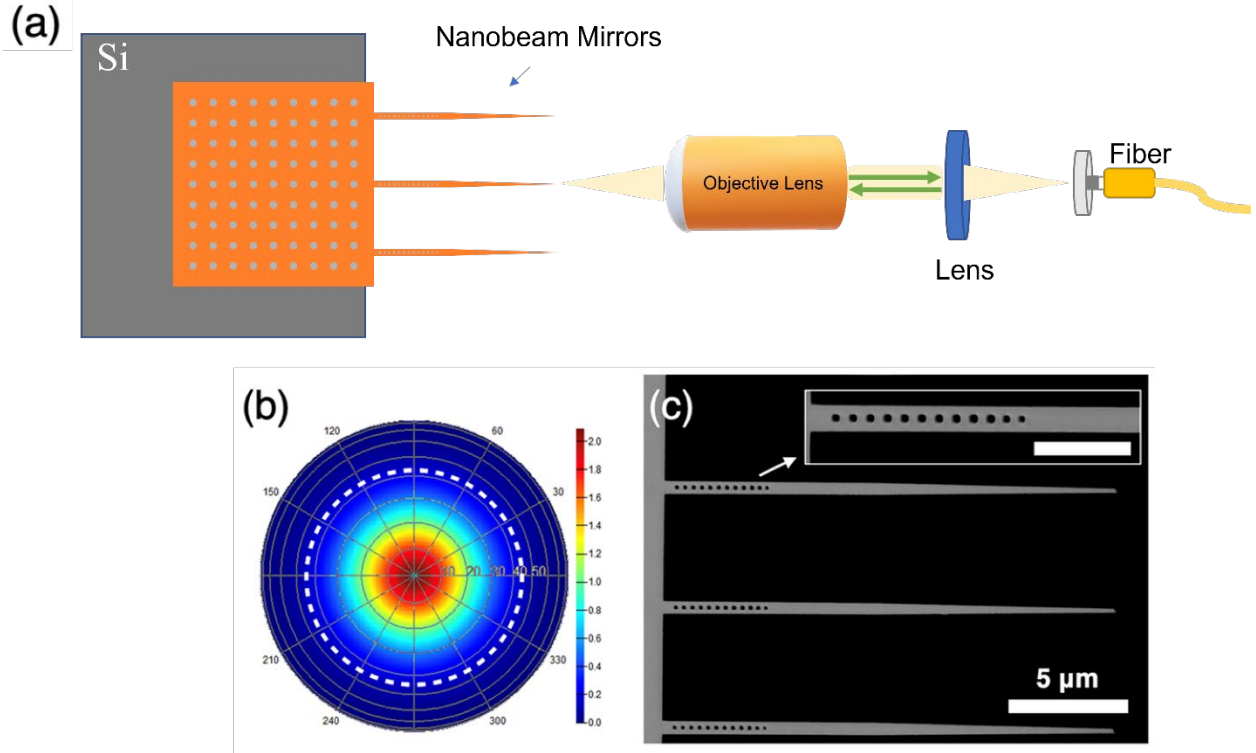


Figure 8. (a) Schematic for the method of efficient coupling from the nanobeam to objective lens and the optical fiber. (b) Far-field mode profile from nanobeam taper using FDTD simulations. White dashed line represents numerical aperture of objective lens. (c) SEM image of the fabricated nanobeam arrays. Each nanobeam waveguide has a photonic crystal mirror in one end and tapered out-coupler on the other end.

The far-field pattern of the nanobeam mode at the linearly tapered end is displayed in Figure 8 (b). We estimated the lens coupling efficiency ( $\eta_{\text{lens}}$ ) as the portion of the far-field emission falling within the numerical aperture of 0.66 represented by the white dashed circle in Figure 8 (b). We examined the taper length dependence of the lens-coupling efficiency and determined that the taper length must exceed  $10\ \mu\text{m}$  to adiabatically increase the nanobeam mode and attain high  $\eta_{\text{lens}}$ . At a taper length of  $10\ \mu\text{m}$ , we achieved a lens coupling efficiency of 90%. After the objective lens, it is crucial that the emitted photons effectively couple to an optical fiber. We calculated the coupling efficiency by assessing the

overlap between the far-field pattern of single photon emission and a Gaussian function [42]. To perform this calculation, we established the taper length at 10  $\mu\text{m}$ , the nanobeam height at 280 nm (the thickness of the InP membrane layer from the wafer used in experiments), and chose the nanobeam width to be 400 nm. We then optimized the Gaussian overlap integral, based on the tip width at the end of the taper. Based on the optimization results, we chose a tip width of 150 nm to achieve a fiber coupling efficiency ( $\eta_{\text{fiber}}$ ) of 91%. Compared with the previous method, in this case, our total coupling efficiency into the fiber would be  $\eta = \eta_{\text{lens}}\eta_{\text{fiber}} \approx 0.82$ , and the brightness into the fiber,  $B$ , would be again  $B = \beta \eta$ . While simulated coupling efficiency into the fiber is lower than in the previous case, experimentally this method is more feasible to produce and does not possess additional fabrication losses such as silicon dioxide and aluminum oxide deposition that were the prevalent loss mechanisms in the previous case.

Using the same fabrication procedure, we fabricated InP nanobeam arrays with InAs quantum dots attached to large rectangular pads. As stated in the previous subchapter, we used a silicon nitride hard mask, electron beam lithography, 2-step reactive ion etching, and wet chemical etching to produce desired structure suspended on the InP sample as shown in Figure 8 (c). However, different from the previous case, we can not use the pick-and-place method with a tungsten probe to transfer these nanobeam arrays, because the size of the entire structure is too big to pick and handle with a tungsten microprobe. For these reasons, we switched to a different method to transfer the new structure safely onto the edge of the silicon piece. We used a 30  $\mu\text{m}$  x 30  $\mu\text{m}$  x 40  $\mu\text{m}$  polydimethylsiloxane (PDMS) stamp to pick-and-place the nanobeam arrays via the square pad as explained in Chapter 1. Once we had successfully detached the nanobeam arrays from the InP substrate, we transfer-printed them onto the edge of a silicon carrier chip. This approach allowed for efficient edge-coupling of the nanobeam waveguides to the objective lens,

and to the fiber from the tapered side of the nanobeams so that we could pump the quantum dots inside the nanobeam and collect the photoluminescence from the same path.

Following the fabrication of the nanobeam structures, we assessed their photon coupling efficiency using an objective lens. The lens coupling efficiency can be determined by measuring the nanobeam's reflectivity, which includes the transmission of optics in the system and the fiber coupling efficiency. We determined that the lens coupling efficiency was 60% for telecom O-band by using a CW laser to probe the nanobeams. As before, it's worth noting that this value is a lower bound of the lens coupling efficiency since we assumed perfect reflectance within the photonic crystal mirror. On the other hand, we also measured fiber coupling efficiency to be around 61%. Together, they make experimental total out-coupling efficiency to be around %36. The discrepancy between this measured value and the simulated lens and fiber coupling efficiencies (90% - 91%) is likely due to several factors, such as the below-unity reflectivity of the photonic crystal mirror, scattering loss from the surface roughness of the tapered out-coupler, and imperfect alignment of the nanobeam with the optic axis.

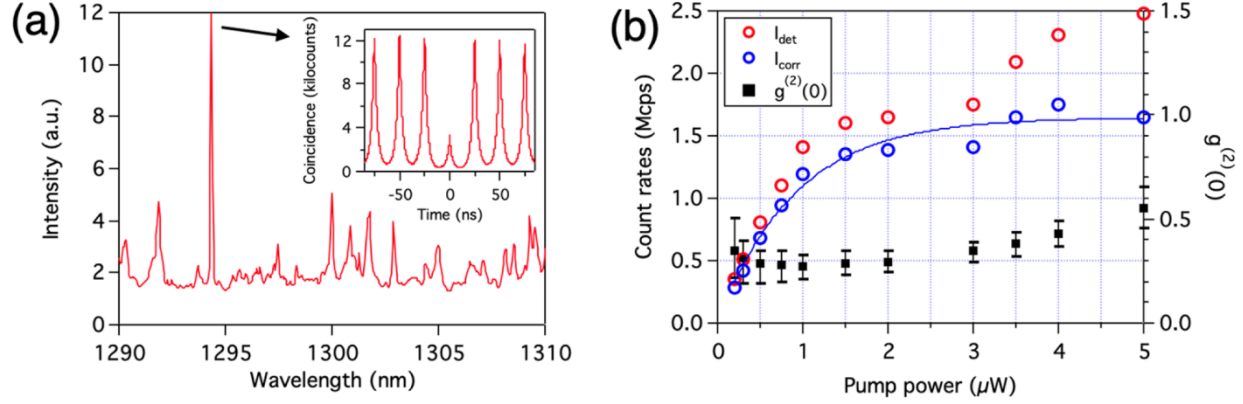


Figure 9. Photoluminescence and second-order auto-correlation measurements from the sample. (a) Photoluminescence spectrum from the nanobeam using above-band excitation with 780 nm pulsed laser. Inset is second-order auto-correlation measurement for the selected bright peak at 2  $\mu$ W. (b) Pump power dependence of count rates and  $g_2(0)$  at superconducting nanowire single photon detectors. Black dots are  $g_2(0)$  values at each pump power. Red circles,  $I_{det}$ , are detected count rates and blue ones,  $I_{corr}$  are corrected ones with  $g_2(0)$ . Blue line is the curve fitted to the corrected count rates with parameters  $I_{max} = 1.65 \pm 0.05$  Mcps and  $P_{sat} = 0.91$   $\mu$ W

Figure 9 shows the photoluminescence and second-order auto-correlation measurements from the nanobeam sample using 780 nm above-band 40MHz pulsed laser and collected and the measurement setup in Appendix A. Figure 9 (a) shows the photoluminescence spectrum from above-band excitation from the selected nanobeam. We choose the bright peak at 1294.3 nm, and measured and found a clear antibunching with  $g_2(0) = 0.26 \pm 0.09$ . In Figure 9 (b), we measured pump power dependence of single photon count rates and  $g_2(0)$  values for the same peak. We corrected the single photon count rates with their respective  $g_2(0)$  values and fit the data to the same equation of  $I(P) = I_0 + I_{max}(1 - e^{-\frac{P}{P_{sat}}})$ . From the fitted data, we found the maximum corrected single photon count rate to be  $I_{max} = 1.65 \pm 0.05$  Mcps at  $P_{sat} = 0.91$   $\mu$ W. From this, we can find the end-to-end efficiency by dividing the  $I_{max}$  to the pulsed laser repetition rate of 40 Mhz. We found the end-to-end efficiency of whole single photon generation and detection to be

$4.1 \pm 0.1\%$ . From this efficiency, and measured optical efficiencies of all of the optics, we can again calculate the brightness into the fiber by dividing end-to-end efficiency with detector efficiency and transmission efficiencies of the fiber-type spectral filter. From these calculations, we found fiber-coupled brightness,  $B$ , to be around  $9.5 \pm 0.1\%$ .

## 2.4 Surface Passivation and Smoothing of InP Nanobeam Cavities

In our previous work, we achieved a notable single photon brightness close to 10% at the telecom O-band; however, this remains relatively low compared to the brightness obtained from InAs quantum dots in GaAs with near-infrared emission [43]. The fundamental differences between our approach and those used for InAs/GaAs quantum dots include cavity-enhanced performance and the advanced fabrication of suspended GaAs photonic structures. In contrast, InP patterning necessitates a high-temperature dry etch process, requiring a hard mask and potentially introducing additional sidewall roughness [44-45].

Device performance is increasingly impacted by surface and interface properties. III-V semiconductor surfaces typically exhibit a high density of surface states within the band gap, leading to nonradiative surface recombination. To mitigate these negative effects on optical and electronic properties, passivation is essential. Sulfide-containing solutions are a common method for passivating III-V surfaces [46], as they remove native oxides and form a passivating layer of sulfides and residual oxides. For InP-based structures, sulfur passivation has been employed on nanowires [47] and InP/insulator interfaces [48-50], generating a passivating layer consisting of In-S bonds and residual indium and phosphorous oxides [50,51].

Surface and interface roughness are increasingly critical factors in numerous nanophotonic devices, as they can result in losses, defects, and even device failure. It is therefore crucial to develop

fabrication methods that either reduce roughness or produce smoother surfaces. One such technique is atomic layer deposition (ALD), which has demonstrated the ability to effectively smooth surfaces while providing precise thickness control and uniform, conformal processing [52, 53].

In this section, we outline our efforts to develop nanobeam cavity-coupled quantum dots that efficiently interface with fiber optics and demonstrate enhanced fabrication quality through surface passivation and smoothing. Our aim is to reduce potential losses and degradation associated with the fabrication of suspended InP structures.

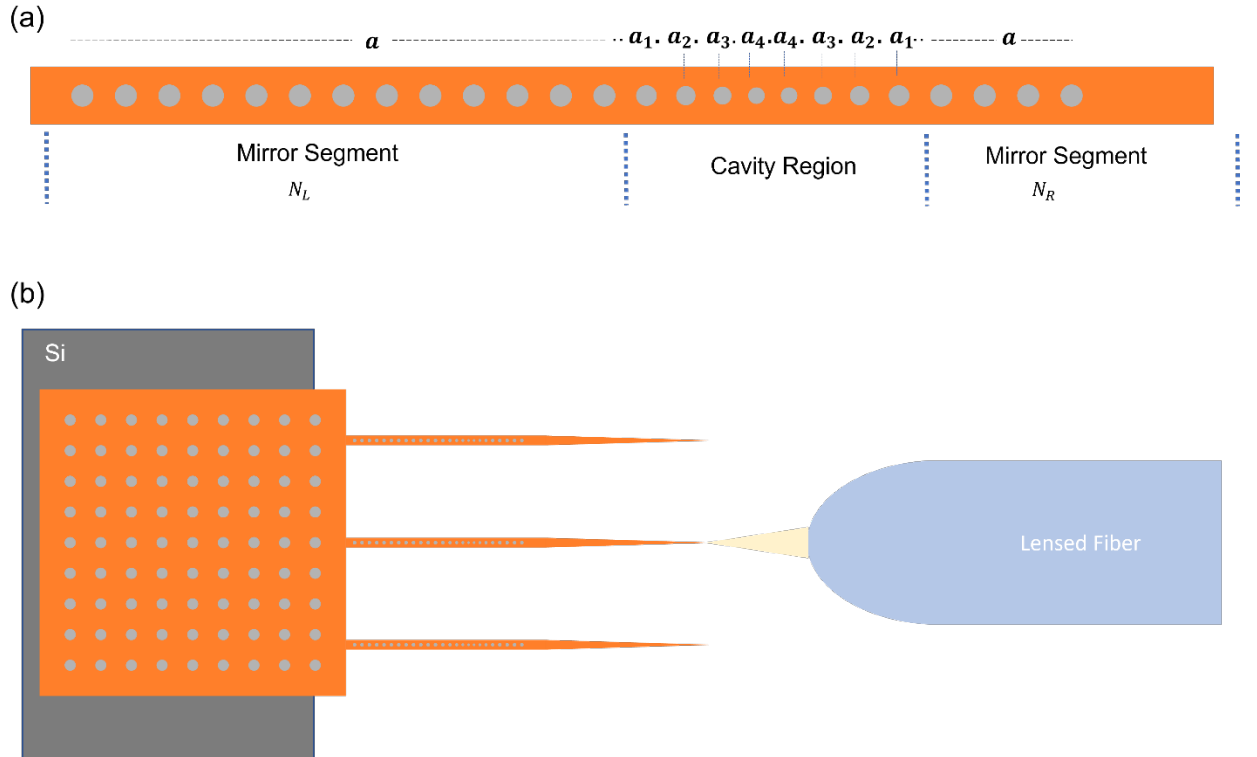


Figure 10. (a) A schematic for a one-sided nanobeam photonic crystal cavity. The cavity consists of one perfectly reflecting mirror segment at the left with  $N_L$  number of mirror holes, one partially reflecting mirror segment at the right with  $N_R$  number of mirror holes, and a cavity region where periods and holes are linearly tapered. (b) Proposed measurement scheme for edge coupling with lensed fiber.

Figure 10 shows the schematic for the proposed nanobeam photonic crystal cavity and measurement scheme. The cavity is realized by tapering and shifting the inner 8 holes between two outer photonic crystal mirrors using finite-difference time-domain simulations. The number of mirror holes on the right mirror segment,  $N_R$ , is varying between 2 and 6 to be partially reflective and allow the cavity to couple into a nanobeam waveguide. The number of mirror holes on the left mirror segment,  $N_L$ , is kept at 9 to be fully reflective towards the other side of the nanobeam waveguide. The lattice parameter,  $a$ , for the mirror side is 360 nm, while the hole radius is  $0.3a$ . In the cavity region, it is linearly tapered to  $a_4 = 270$  nm. Figure 10 (b) shows the new measurement schematic where after some modification in our cryostat, instead of coupling to the objective lens and then fiber, we directly couple the light into a lensed fiber. This method avoids additional losses coming from the objective lens and other mirrors from the previous method. While we did not measure the single photon brightness yet, reflectivity measurements routinely give nanobeam-fiber coupling around 50-60%.

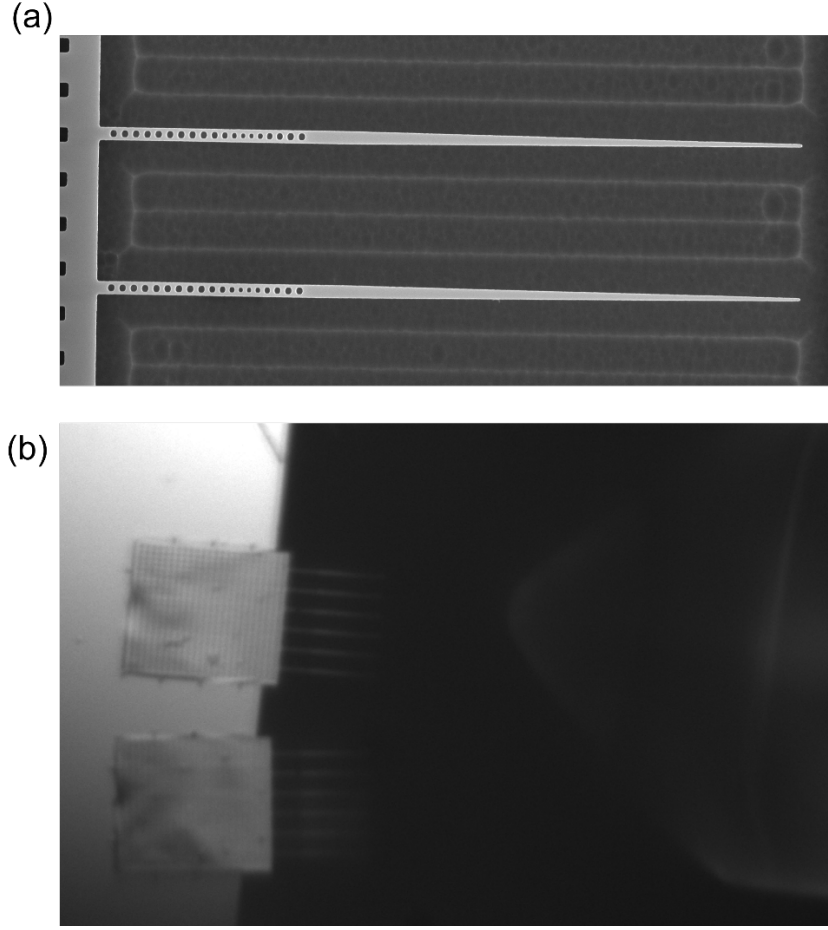


Figure 11. (a) SEM image of the fabricated nanobeam photonic crystal cavities with a tapered end. (b) Optical microscope image of a lensed fiber probing the nanobeam cavities that are transfer-printed at the edge of a silicon piece.

Figure 11 shows a SEM image of the final suspended nanobeam cavity array attached to a large pad on InP, and an optical image of the transferred nanobeam arrays and lensed fiber. We used the same fabrication method as in previous chapters to pattern InP. However, different from the previous fabrication, in the wet-etch process where we use HCl solution to remove the sacrificial layer, we also use it to remove native oxides on the InP pattern. After that, while we keep one sample with usual recipe, we dip the other one in additionally into aqueous solution of ammonium sulfide followed by 2 nm thick deposition of  $Al_2O_3$  using ALD. After fabricating these nanobeam cavity arrays in two samples, we

transfer them onto the edge of a silicon piece for measurement using PDMS stamp-based transfer-printing method as explained in the previous chapter. The nanobeam cavities were then probed with a lensed fiber as shown in Figure 11 (b).

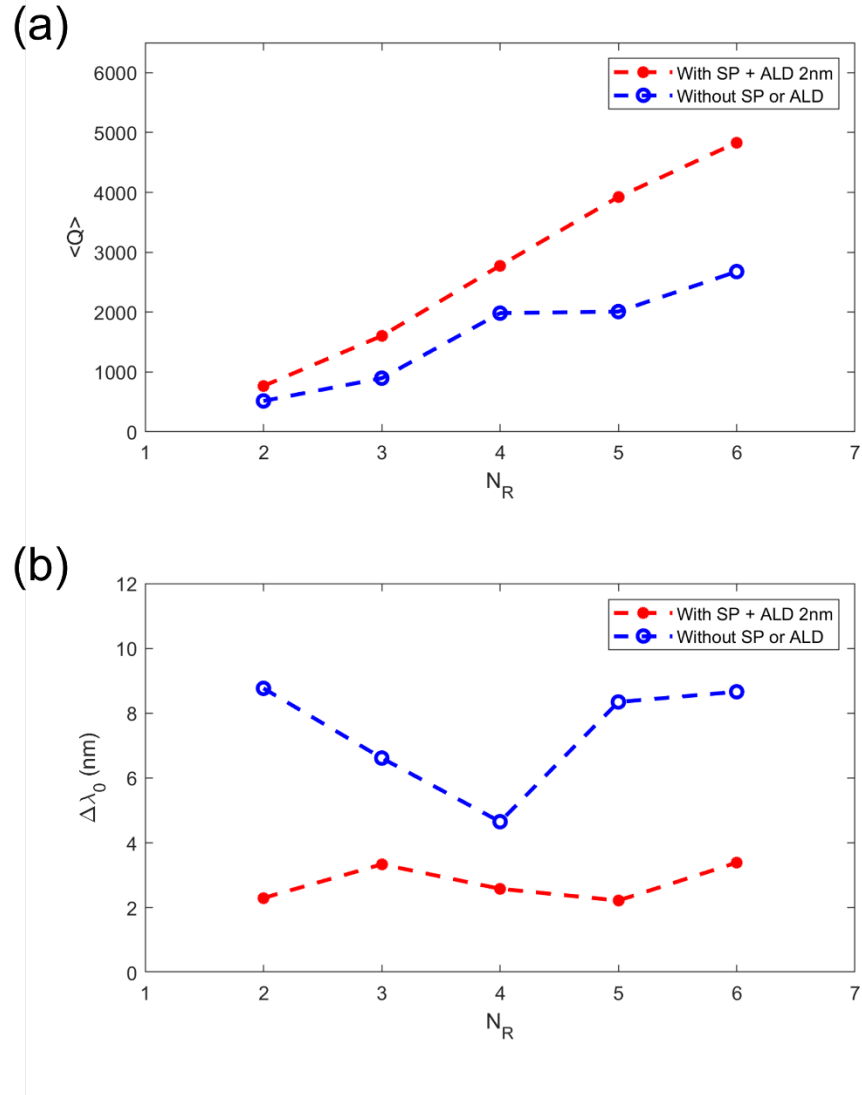


Figure 12. Measured Quality Factor from Nanobeam Cavities with/without Surface Passivation (SP) and 2nm ALD.  $N_R$  stands for the number of mirror holes on the right side of the cavity where the cavity is coupled to the waveguide. (a) Average quality factor over approximately 10 nanobeam cavities with respect to number of holes

in the right side of the cavity. (b) Average deviation for cavity resonance over approximately 10 nanobeam cavities with respect to the number of holes in the right side of the cavity

Figure 12 shows the measurement results from cavity characterization from reflectivity measurements. We probed around 10 nanobeams for each  $N_R$  from each sample using a broadband white light and calculated the parameters for the cavity from cavity reflectivity. Figure 12 (a) shows the mean of quality factors for each  $N_R$  from the sample with surface passivation and ALD (red), and the sample without any additional process (blue). We observed between 60%-100% increase in the quality factor from the cavities from surface passivated and smoothed samples compared to the ones without passivation and ALD process. We also observe a reduction in the deviation of cavity center wavelengths in nanobeam cavities from the processed sample compared to the usual sample where the deviation is reduced from the 6-9 nm range to near 2 nm as shown in Figure 12 (b).

Enhancement in the quality factor and reduction in cavity center variation suggest decent improvement in the surface quality of nanobeams due to the passivation and smoothing. There are still some open parameters in the ongoing optimization process for these recipes, however, current results are already quite an improvement compared to the fabrication results for other suspended InP photonic crystal cavities.

## 2.5 Conclusion

In this chapter, we explained our advancement in efficiently integrating InAs/InP quantum dots with fiber-optics as telecom wavelength single photon source. Two methods were employed to couple quantum dot single photon sources to fiber-optics. In the first method, a nanobeam waveguide containing quantum dots, a photonic crystal mirror, and a linear taper is placed on top of a fiber-taper in order to adiabatically couple light from the nanobeam taper to the fiber taper. This method did not require precise

free space optical alignment or careful positioning of the fiber taper with respect to the quantum dots. The system achieved a fiber-coupled brightness of 1.4% with  $g_2(0)$  value around 0.17 and could potentially elevate the brightness to as high as the simulated value of 88% by improving the efficiency through surface treatment or employing a flame-pulled fiber.

In the second method, we engineered the tapered end of the nanobeam to efficiently collect light into the objective lens, and couple it into the fiber. This method achieved a fiber-coupled brightness of  $9.5 \pm 0.1\%$  using above-band excitation with  $g_2(0)$  value around 0.25. The indistinguishability of single photons can be further improved by resonant pulsed excitation or coupling to a cavity to enhance the spontaneous emission rate. Compared with the results obtained from InAs/GaAs quantum dots coupled to cavities in the near infrared regime, we observed 3 or 4 times less brightness from these two methods. To further improve efficiency, we designed a one-sided nanobeam photonic crystal cavity instead of the mirror in the nanobeam waveguide to couple quantum dot emission to the cavity mode to enhance the spontaneous emission rate. To that end, we also considered improving our InP fabrication with surface passivation and smoothing in order to reduce losses coming from surface defects and roughness. For that purpose, we used a sulfuric surface passivation process followed by atomic layer deposition of aluminum oxide that can both reduce native oxides appearing on the surfaces of nanobeam and smooth the sidewall roughness. From this process, we observed up to 100% enhancement in the quality factor of our nanobeam cavities which suggests quite an improvement in surface treatments of the nanobeams. Our next step would be coupling quantum dots to these new surface treated nanobeam photonic crystal cavities to reach the full potential as a telecom wavelength bright single photon source. These promising results suggest the possibility of achieving bright and indistinguishable telecom-wavelength photons efficiently integrated with fiber-optics, which are essential for scalable quantum networks and photonic quantum computers.

## Chapter 3. Integration of Quantum Dots for Tunable Single Photon Sources in Silicon Photonic Circuits

### 3.1 Introduction

Photonic integrated circuits (PICs) have emerged as a powerful platform for realizing large-scale quantum photonic information processing. Among the various PIC technologies, silicon photonics is one of the most attractive platforms for implementing large-scale PICs due to its compatibility with mature complementary-metal-oxide-semiconductor (CMOS) technology. Silicon quantum photonics exploits the power of silicon photonics and provides a fascinating route for large-scale photonic quantum information processing [17,18, 20, 25]. However, current silicon quantum photonics inherently lacks scalability due to the probabilistic nature of single-photon sources (SPSs) that have been implemented on silicon [18, 25].

Despite these challenges, recent advances have been made in the development of hybrid integration approaches such as epitaxial heterogrowth, wafer bonding, and pick-and-place [25]. These methods provide a potential solution by incorporating disparate photonic technologies into a single integrated system that may not be otherwise compatible with a single fabrication process. In the context of quantum technologies, hybrid integration offers the tantalizing goal of bringing together quantum emitters, quantum memories, coherent linear and nonlinear operations, and single-photon detection into a single quantum photonic platform [25]. In particular, self-assembled quantum dots are highly promising because of their proven potential to deterministically emit single photons with high purity and indistinguishability [21]. The QDs can be engineered to emit single photons in the telecom band, where silicon is optically transparent. However, the hybrid integration of QDs is inherently difficult, as the

random position and emission wavelength of each epitaxial QD hinder the deterministic integration of a desired QD on a proper position of the target PIC.

The difficulty becomes more pronounced when utilizing conventional heterogeneous integration techniques, such as wafer bonding and direct epitaxial growth. Thus far, there are only a few reports on the integration of QD-based SPSs on silicon-based photonic platforms, and none of them have been implemented on a silicon waveguide that was processed using a standard CMOS fabrication technology [25]. Pursuing a means of fusing fully CMOS-processed silicon photonics chips with QD SPSs is imperative for leveraging the power of silicon photonics.

In this chapter, we introduce our advances in large-scale integration telecom wavelength InAs/InP quantum dots with CMOS-processed silicon photonic chips in order to generate multiple on-chip tunable QD-based single photon sources that can be used for on-chip quantum information processing. For this purpose, we collaborate with Prof. Dirk Eungland from MIT, and AIM Photonics Foundry for the integration of InAs/InP quantum dots with CMOS-processed silicon photonic circuits.

### 3.2 Hybrid-Integration of Telecom Quantum Dots with photonic integrated chips with Adiabatic Coupling

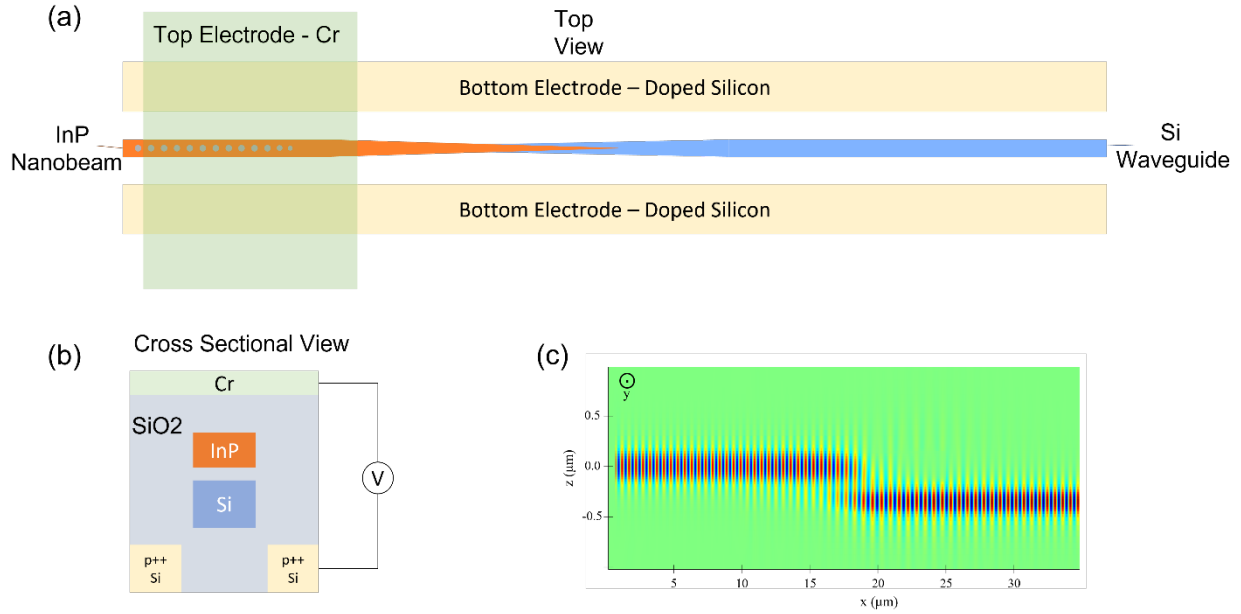


Figure 13 (a) A schematic for the top view of the proposed method. (b) Cross-sectional view of the proposed method. (c) Electric field mode profile from FDTD simulation result for coupling between InP nanobeam taper to Silicon Waveguide taper.

Figure 13 illustrates hybrid architecture where an InP nanobeam containing InAs quantum dots integrated with a silicon-on-insulator photonic integrated circuit to adiabatically couple single photon emission from tunable quantum dots into a silicon waveguide on the chip. Figures 13 (a) and (b) show the top view and cross-sectional view of the ‘quantum socket’ of the architecture where InP nanobeam waveguide with photonic crystal mirror and a tapered end adiabatically coupled into silicon waveguide with its taper. We have two p-doped silicon electrodes below the silicon waveguide and a top Cr electrode. Applying voltage through these electrodes creates an electric field on the InAs quantum dots

in InP nanobeam in order to tune exciton emission with the quantum confined Stark effect [54-56]. This is only a small section of the entire chip where light is extracted from the silicon waveguide to the lensed fiber via silicon edge-couplers. Figure 13 (c) shows the FDTD simulation results for the electric field mode profile. We observed around 95% coupling into silicon waveguide from InP nanobeam for the optimized parameters where InP waveguide thickness is 500 nm, silicon waveguide thickness is 400 nm, InP taper length is 15  $\mu\text{m}$ , silicon taper length 40  $\mu\text{m}$  and oxide gap between the InP and silicon is 100 nm.

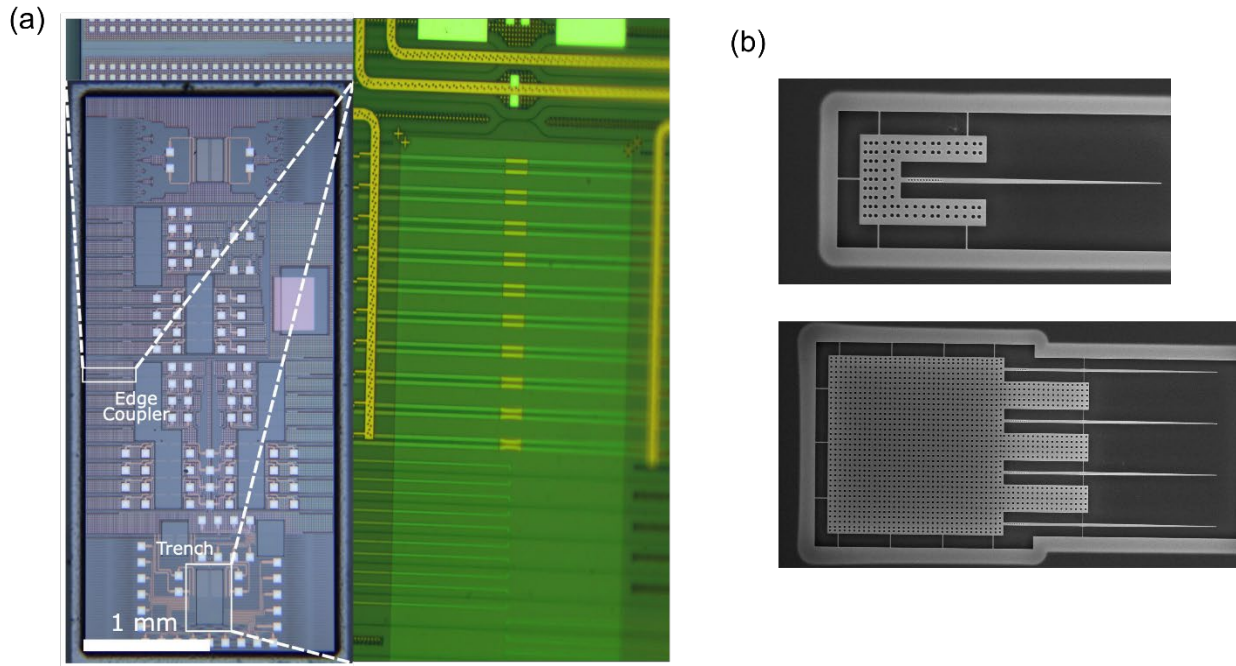


Figure 14. (a) Optical microscope image of the PIC. (b) SEM images for the fabricated InP nanobeams with small and large pads.

Figure 14 shows the optical and SEM images from foundry-made PIC and InP nanobeams. The production of PICs took place at AIM Photonics' foundry, utilizing 193 nm deep ultraviolet water-immersion lithography. This process allows for the large-scale production of SOI PICs on 300 mm wafers, incorporating multiple metal and dielectric layers as well as lateral p and n-type doping. For the

o-band-specific PIC, a process development kit (PDK) element was utilized to design broadband optical edge couplers with a low loss rate of below 3 dB over the 1260-1360 nm wavelength range [57]. Additionally, other components were custom designed to ensure optimal operation within the o-band. Figure 14 (a) shows the optical microscope image of one of the diced PICs. Zoomed in the image at the top shows the edge couplers which we use to couple light into a lensed fiber. Zoomed in the image at the right shows an array of the quantum socket where tapered silicon waveguides and p-doped silicon electrodes lay. Figure 14 (b) shows the SEM images of InP single and multiple nanobeams containing InAs quantum dots. We use the same wafer from the previous chapters. As in previous chapters, the fabrication of nanobeams is done by electron beam lithography, reactive ion etching, and wet etching.

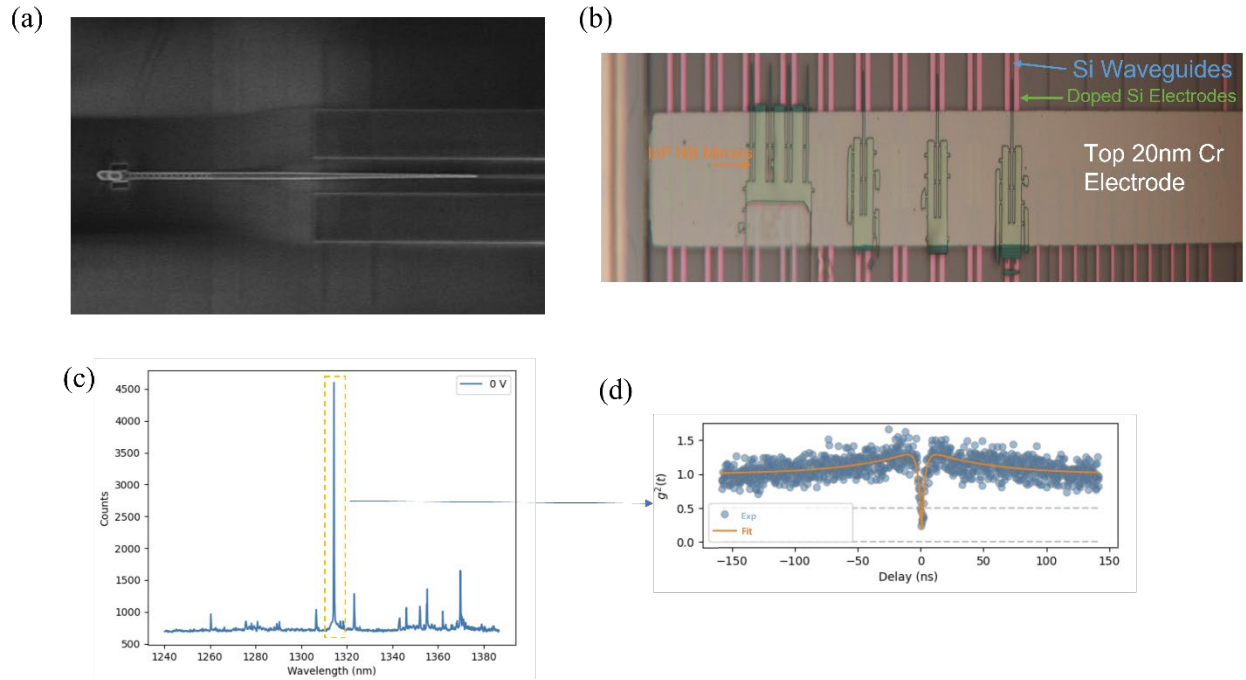


Figure 15 (a) SEM image of an InP nanobeam transferred on a quantum socket using a tungsten probe and pick-and-place method. (b) Optical microscope image of InP nanobeams transferred on quantum sockets using a PDMS stamp and transfer-printing method (c) Photoluminescence spectrum from quantum dots in the third single nanobeam in (b). (d) Second-order autocorrelation measurement for the selected bright dot emission in (c).

After InP nanobeams and foundry-made PIC chip fabrication, we started the hybrid integration of nanobeams on quantum sockets in the PIC. Figure 15 (a) shows the SEM image of the initial trials where we pick-and-placed the nanobeam on a quantum socket using a tungsten microprobe inside the SEM/FIB machine. While we could realize high precision and accuracy for taper-taper position using this method, it was too time consuming and difficult due to the charging effect of SEM imaging on silicon dioxide layers. Therefore, for rapid integration of nanobeams, we switched our method to transfer-printing with a large PDMS stamp. Figure 15 (b) shows the optical microscope image of the transferred single nanobeams and nanobeam arrays using the PDMS stamp where we could still get taper-taper integration close to the previous method with a little bit of careful positioning and transfer a large number of nanobeams easily. After the transfer, nanobeams are buried in 500 nm silicon dioxide followed by a deposition of 20 nm Cr as the top electrode using optical lithography. The sample is then loaded into a cryostat in which we can optically excite quantum dots inside the nanobeam from the objective lens and collect the emission coupled into the PIC silicon waveguide through lensed fiber. Figure 15 (c) shows the photoluminescence spectrum from the third single nanobeam in Figure 15 (b). We selected the bright quantum dot peak in the spectrum at 1318.5 nm and performed a second-order autocorrelation measurement using the same methodology as in previous chapters. Figure 15 (d) shows the histograms representing this correlation in the form of a second-order correlation of  $g_2(\tau)$  where we observed  $g_2(0)$  value of 0.17 from the fitted data.

### 3.3 Tunability of Quantum Dots inside the integrated nanobeams

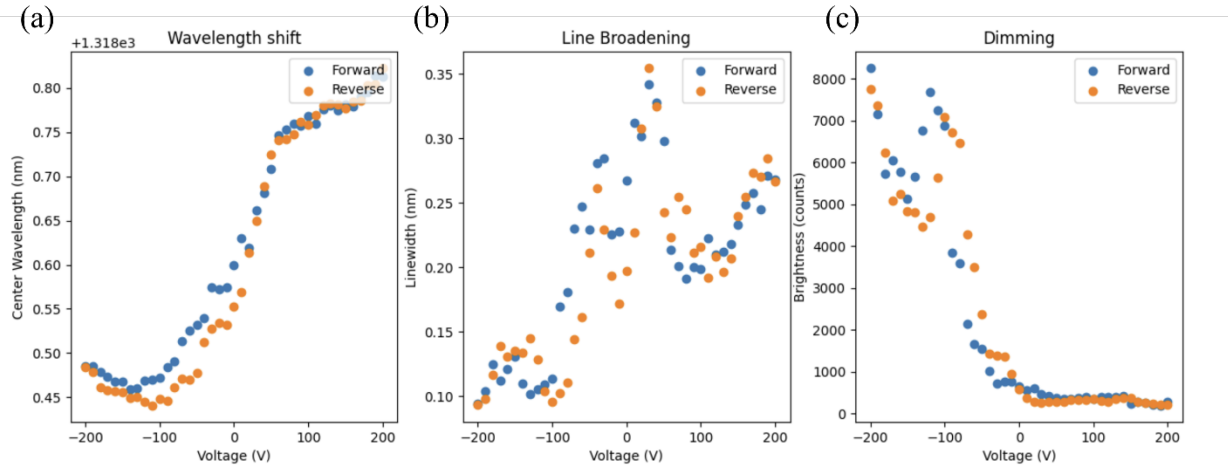


Figure 16. Tunability results from applied voltage over top and bottom electrodes. (a) Wavelength shift with respect to increasing and decreasing applied voltage. (a) Change in the linewidth of the quantum dot emission with respect to the applied voltage. (c) Count rates with respect to the applied voltage.

Figure 16 shows the tunability results of the bright quantum dot peak with applied voltage over top Cr and bottom doped silicon electrodes. Overall, we observed close to 0.5 nm wavelength shift with quantum confined stark effect as shown in Figure 4 (a). Figure 16 (b) shows the changes that occurred in the linewidth of the quantum dot peak with the applied electric field. Integrated PL intensity from the quantum dots is shown in Figure 16 (c) where we observed dimming of emission with increased voltage similar to our previous stark shift results from the same quantum dot wafer [56].

### 3.4 Conclusion

We have presented a platform for integrating tunable single-photon emitters on large-scale PICs. By heterogeneously integrating InAs/InP chiplets with a cutting-edge silicon-on-insulator PIC, we have demonstrated scalable emission wavelength programmability with individual emitter resolution. Since

we observed a limited spectral tuning compared to our previous results [56] and larger linewidths of quantum dot peaks, future work should consider probing quantum dot emission in each step of fabrication to deduce the effect of each step on the quantum dot emission. These measurements could result in a refined post-processing workflow that narrows the emission linewidths of quantum dots, reducing charges and paving the way for highly-tunable and lifetime-limited on-chip single photon sources at telecom wavelengths.

To increase the number of integrated nanobeams, a scalable transfer method is necessary, which can build upon existing techniques used for large-scale heterogeneous integration of other light sources like colloidal quantum dots and lasers [25]. Devices featuring a large number of emitters could contribute to more advanced on-chip multi-photon quantum systems that may also benefit from active components facilitated by the platform, such as RF electronics or cryogenics-compatible optical modulators [58]. Incorporating other components like on-chip SNSPDs could further enable more intricate types of on-chip photonic quantum computations [59,60]. To sum up, the integration of photonic and atomic systems on a scalable platform paves the way for a new era of programmable quantum information processors.

# Chapter 4. Low Power Optical Bistability Quantum Dots-Coupled to Nanobeam Cavity

## 4.1 Introduction

Optical bistability is a widely researched nonlinear optical phenomenon where the output light intensity from an incident light on a photonic medium exhibits hysteresis [61]. The hysteresis in the output light intensity is the result of two stable electromagnetic states that can be exploited in various applications, such as optical switches [62], memories [63], and differential amplifiers [64]. However, the integration of such applications on a large scale requires optical nonlinearity at low power levels, fast modulation speeds, and photonic designs with small footprints that are compatible with silicon photonic circuits [65].

To meet these requirements, various photonic platforms have been used to demonstrate low-power optical bistability, including slab waveguide gratings [66], photonic crystal cavities [67], micropillars [68], and microring resonators [69]. Different nonlinear media, such as saturable absorbers [70], kerr nonlinearities [71], and thermo-optic materials [72-74], have been used in these photonic platforms to demonstrate optical bistability. Thermo-optic devices, in particular, rely on the thermally induced refractive index change, which occurs due to heating in the medium due to optical absorption. The materials used in these devices must have high absorption coefficients and strong thermo-optic effects to realize low-power optical bistability. By incorporating an absorptive medium into nanophotonic architectures that have strong light and heat confinement in a small mode-volume, the power threshold for thermally induced optical bistability can be reduced [75-78].

In the following section, we will show how to achieve low-power thermo-optical bistability using high-density quantum dots that are coupled to an optical fiber [98]. We will start by discussing the theory

of thermo-optical bistability in an optical cavity with a thermo-optic absorber. We will then explain why high-density quantum dots a suitable candidate are for realizing this nonlinearity. Finally, we will demonstrate how we have achieved low-power optical bistability using quantum dots in a nanobeam cavity.

## 4.2 Theory of Thermo-Optical Bistability

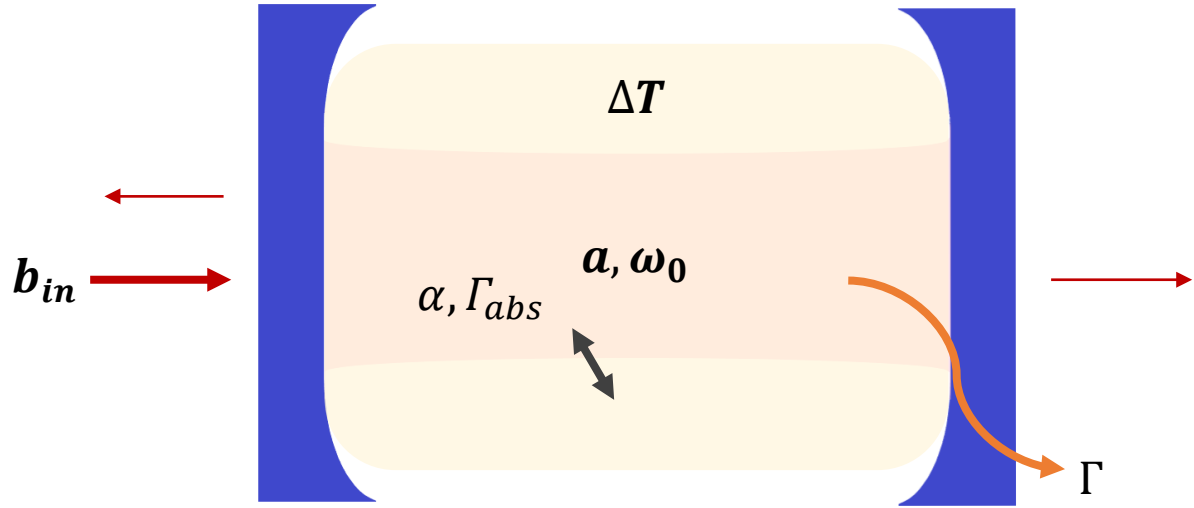


Figure 17. A schematic of a leaky optical cavity with thermo-optical absorber

In this part, we will give a simple overview for theory of thermo-optical bistability in order to understand the parameters and mechanism behind material, and design choice in the later parts. Figure 17 shows an illustration of a thermo-optical cavity. It is a leaky optical cavity with a thermo-optical absorber. In this case, we can write the thermos-optical dynamics of cavity field following input-output formalism as below.

$$\frac{da(t)}{dt} = \left( i\Delta\omega - \frac{\Gamma}{2} \right) a(t) + i\omega_0\alpha\Delta T(t)a(t) + \sqrt{\eta\Gamma}b_{in}(t)$$

(1)

$$C_p \frac{d\Delta T(t)}{dt} = \Gamma_{abs} |a(t)|^2 - K\Delta T(t) \quad (2)$$

Where,  $a(t)$  and  $b_{in}(t)$  are annihilation operators for cavity field and incident field.  $\Delta T(t)$  is effective temperature difference.  $C_p$ ,  $K$ , and  $\alpha$  are heat capacity, heat conductivity and thermo-optic coefficient respectively.  $\Gamma_{abs}$  is the linear absorption rate that contributes to the heat increase in the cavity. Here, we did not consider other nonlinear absorption rates for simplicity.  $\Gamma$ ,  $\eta$ , and  $\omega_0$  are cavity decay rate, coupling efficiency to the cavity and the frequency of the bare cavity resonance. Equation (1) describes the dynamics of the cavity field mode, under incident field and thermo-optical refractive index change. Equation (2) describes the dynamics of temperature difference of the cavity from ambient temperature under optical absorption. In steady state and under incident field with frequency  $\omega_L$ , we can derive the following equations for the cavity field operator and temperature.

$$a = \frac{\sqrt{\eta\Gamma}}{i(\Delta\omega - \alpha\omega_0\Delta T) + \Gamma/2} b_{in} \quad (3)$$

$$\Delta T = \frac{\Gamma_{abs}}{K} |a|^2 \quad (4)$$

Where  $\Delta\omega = \omega_L - \omega_0$  is detuning between the incident field and the cavity mode. Combining these two equations, we arrive at the following relations for the cavity field and input power.

$$\frac{|a|^2}{|b_{in}|^2} = \frac{4\eta/\Gamma}{1 + \left(\frac{2\Delta\omega}{\Gamma} + \frac{|a|^2}{|a_b|^2}\right)^2} \quad (5)$$

$$|a_b|^2 = -\frac{K\Gamma}{2\alpha\omega_0\Gamma_{abs}}$$

(6)

Where  $|a_b|^2$  is defined as the characteristic bistability energy [90]. Equation (5) has bistable solutions in the region where  $\Delta\omega < -\sqrt{3}\Gamma/2$ , and cavity mode field intensity has reached to the the  $|a_b|^2$ .

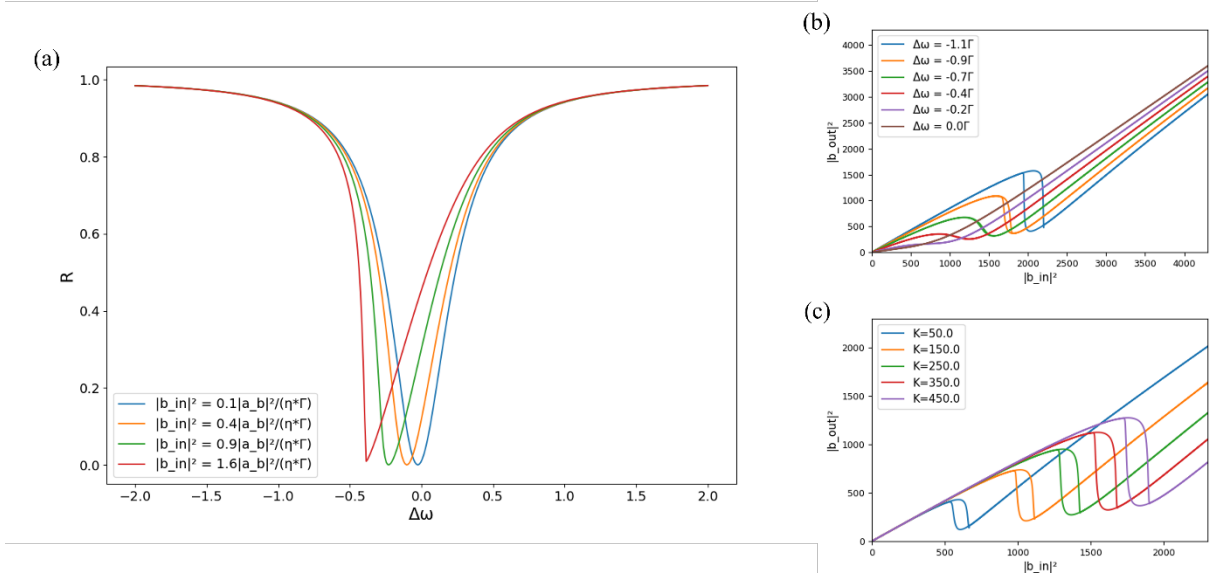


Figure 18. Numerical results from the simple theory of thermo-optical bistability. (a) Cavity reflectivity with respect to detuning ( $\Delta\omega$ ) for increasing input power  $|b_{in}|^2$ . (b) Input-output power relation for different detuning ( $\Delta\omega$ ). Hysteresis observed after satisfying the condition  $\Delta\omega < -\sqrt{3}\Gamma/2$ . (c) Input-output power relation for different heat conductivity ( $K$ ). Increasing bistability threshold is observed with increasing heat conductivity, since  $|a_b|^2$  is linearly dependent on  $K$ .

The results obtained from equations (1)-(5) are displayed in Figure 2. In (a) of the Figure 18, the steady state cavity reflectivity is plotted for various levels of incident power. It can be observed that the cavity reflectivity shifts due to the thermos-optic effect, becoming asymmetric when the incident field intensity exceeds the bistability threshold for the cavity mode intensity. In (b) of the Figure 18, the input-output relations between incident field intensity  $|b_{in}|^2$  and reflected output field intensity  $|b_{out}|^2$  are

shown for different amounts of detuning  $\Delta\omega$  of incident light. In (c) of the same figure, the same input-output relations are displayed under the same detuning but with different heat conductivity values. It can be observed that increasing heat conductivity leads to a higher threshold incident power required to reach bistability, as  $|a_b|^2$  is directly proportional to heat conductivity.

These results indicate that several important parameters must be considered when determining the power levels required to reach optical bistability, including heat conductivity of the cavity, thermo-optical absorption of the light inside the cavity, thermo-optic coefficient of this absorption, and cavity linewidth or Q factor. Equation (6) indicates that lower heat conductivity, higher thermo-optical absorption, and quality factor of the cavity are crucial in choosing the material and photonic design for the cavity. Additionally, while thermo-optical absorption and thermo-optic coefficient are directly related to the material choice, the heat conductivity is determined by both the material and design of the photonic cavity [90].

### 4.3 High Density Quantum Dots for Thermo-optical Bistability

Semiconductor quantum dots are a promising choice for generating thermally induced optical bistability as they possess high absorption coefficients, efficiently converting light to heat [72, 80]. They are grown within a dielectric substrate that can be lithographically patterned into nanophotonic designs, further enhancing optical nonlinearities from quantum dots [68, 72, 81-82]. With strong free carrier confinement and a small diffusion length [83], they facilitate the rapid thermal escape of carriers inside the small mode-volume of nanocavities. Previous realizations of optical bistability using quantum dots have been demonstrated in micropillar cavities [68] and 2D photonic crystal cavities [72]. However, these realizations failed to enhance the thermo-optical properties of quantum dots, either by suppressing

thermal effects through cryogenic cooling [68] or relying on poor thermal isolation in 2D photonic crystal cavities [72], resulting in higher power thresholds for optical bistability compared to other materials [78]. In contrast, 1D photonic crystal nanocavities were used to demonstrate thermally induced optical bistability in silicon at low power levels of a few microwatts due to efficient confinement of light and heat within a small mode-volume [78]. Improved light and heat confinement can significantly enhance thermo-optical nonlinearities from nanocavities with quantum dots.

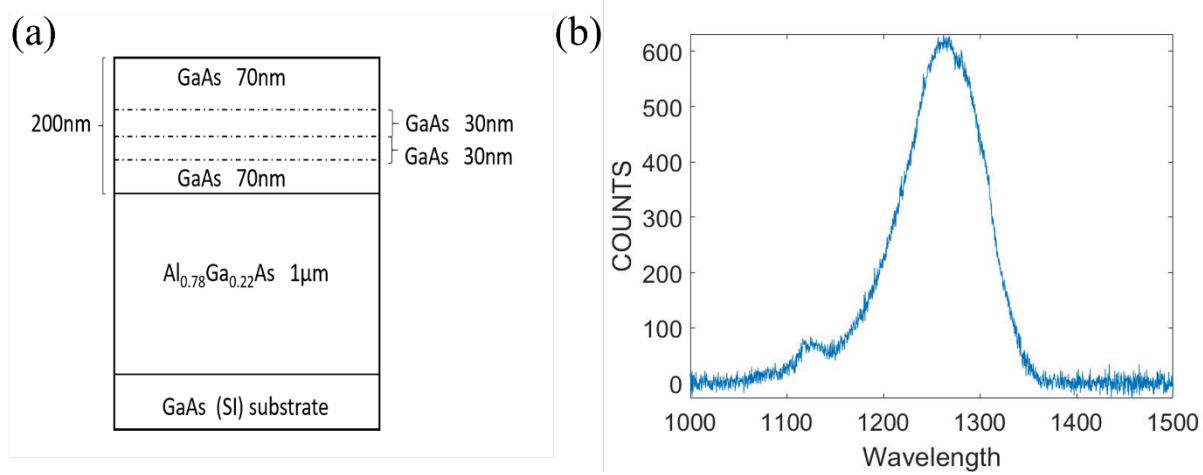


Figure 19. Quantum Dots wafer information. (a) Layered structure of quantum dot wafer. (b) Photoluminescence emission from bulk quantum dot wafer under above-band excitation with 780nm CW laser

The layered structure of high density InAs/GaAs quantum dots and their corresponding micro-photoluminescence emission are illustrated in Figure 19. The wafer is comprised of a 200 nm thick GaAs membrane with three layers of InAs quantum dots, which are situated above a 1 μm thick AlGaAs sacrificial layer. Each layer of quantum dots has a density of  $1 \times 10^{10} \text{cm}^{-2}$  and exhibits room temperature photoluminescence centered around 1280 nm, with a 60 nm inhomogeneous broadening, as shown in Figure 19 (b). This particular wafer is well-suited for our purposes due to the fact that InAs quantum dots possess a low thermal conductivity of around 0.05(W/m-K) in GaAs membrane with thermal conductivity of 44(W/m-K) [95], which is significantly lower than materials such as Silicon

whose thermal conductivity varies around 100-140(W/m-K) at room temperature. Consequently, most of the light absorption and thermal escape transpires near the InAs quantum dots, resulting in the effective localization of generated heat in the absorption region. This characteristic is particularly promising when considering enhancing thermos-optical nonlinear interaction with a small-mode volume cavity.

#### 4.4 Device Structure, Simulations and Hybrid Fabrication

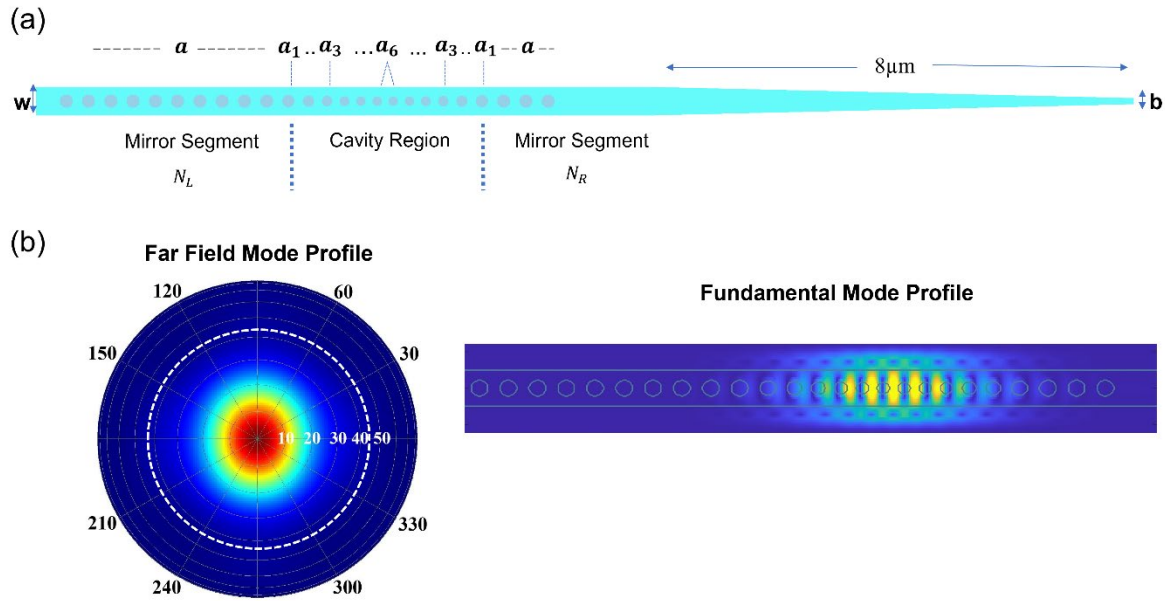


Figure 20. (a) The tapered nanobeam photonic crystal cavity design with lattice parameter  $a = 365$  nm, hole radius  $r = 0.29 a$  and  $r_{1..6} = 0.29 a_{1..6}$ . Number of holes in the mirror segments on right and left side are  $N_R = 4$  and  $N_L = 9$  respectively. The cavity region is realized by tapering and shifting 12 holes located between two mirror segments. The width of the nanobeam waveguide is  $w = 480$  nm and width of taper end is  $b = 150$  nm. Nanobeam width is adiabatically reduced from 480nm to 150 nm at the end of the  $8\mu\text{m}$ -long taper. Thickness of the nanobeam is 200 nm. (b) The far field mode profile from the nanobeam taper and fundamental mode profile of the cavity is shown here. White dashed line in far field profile corresponds to numerical aperture of 0.7 of the objective lens.

Figure 20 illustrates the design for nanobeam photonic crystal cavity. The device consists of a one-dimensional air-cladded GaAs nanobeam photonic crystal cavity with an adiabatic waveguide taper in one side for out-coupling to an objective lens (Figure 20 (a)). The cavity is realized by tapering and shifting inner 12 holes between two outer photonic crystal mirrors using finite-difference time-domain simulations. The number of mirror holes on the right mirror segment,  $N_R$ , is reduced up to 4 to enable light to couple into the cavity from one-side. The number of mirror holes on the left mirror segment,  $N_L$ , is kept at 9 to be fully reflective towards the tapered side of the nanobeam waveguide. For  $N_R = 4$ , simulated quality factor for the cavity resonance at 1280 nm is 229250. Figure 20 (b) shows the fundamental mode profile of the cavity and the gaussian far field mode profile from the nanobeam taper. Fundamental mode profile shows that mode volume is confined in a small region of  $\sim 0.6 \times (\frac{\lambda}{n})^3$ . The adiabatic taper at the end of nanobeam waveguide is designed to have a gaussian mode profile in far field simulation for efficient coupling to an objective lens. Far field mode profile has a coupling efficiency over 90% to the objective lens with a numerical aperture (NA) of 0.7 depicted as white dashed lines in Figure 20 (b).

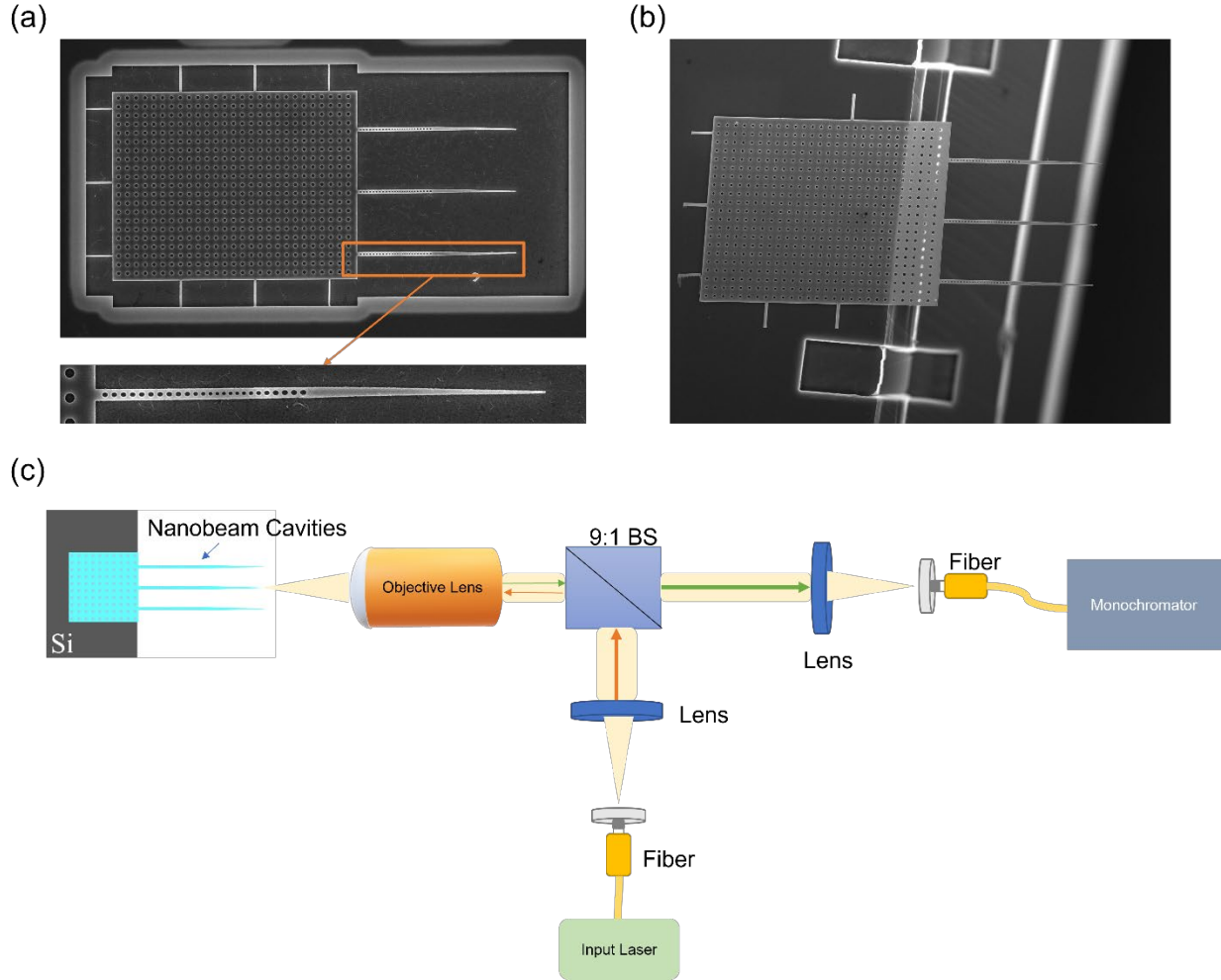


Figure 21. (a) SEM image of a nanobeam array, attached to a pad that is suspended with support bridges. (b) SEM image of the transferred nanobeam array, suspended at the edge of a silicon carrier chip. (c) A schematic of the measurement setup for the transferred nanobeam array.

To realize the proposed device, we used a hybrid fabrication approach. First, we fabricated arrays of nanobeam cavities on a suspended GaAs membrane embedded with InAs quantum dots. This process starts with an InAs/GaAs quantum dot wafer that is grown by molecular beam epitaxy. The wafer consists of 3 layers of InAs quantum dots embedded in a 200 nm thick GaAs membrane on top of a 1  $\mu\text{m}$  thick AlGaAs sacrificial layer as explained in the previous chapter. Using electron beam lithography, we patterned arrays of nanobeam cavities that were connected to large square

pads on one end and tapered ends on the other. Subsequently, hydrofluoric acid solution was employed to remove the AlGaAs sacrificial layer, producing a suspended structure, as displayed in Figure 21 (a) by scanning electron microscopy (SEM). The structure consisted of 3 nanobeam cavities connected to a  $30\text{ }\mu\text{m} \times 30\text{ }\mu\text{m}$  pad area

In the second part of the fabrication process, we used a  $30\text{ }\mu\text{m} \times 30\text{ }\mu\text{m} \times 40\text{ }\mu\text{m}$  polydimethylsiloxane (PDMS) stamp to pick-and-place the nanobeam arrays via the square pad [84-86]. After successfully removing the nanobeam arrays from the GaAs substrate, we transfer-printed them onto the edge of a silicon carrier chip. Figure 21 (b) shows an SEM image of the finalized device with arrays of nanobeam cavities suspended from the edge of the carrier chip. This method enables nanobeam waveguides to be efficiently edge-coupled to the objective lens from the tapered side. It also provides our device an easy way for rapid integration with other on-chip or off-chip photonic circuits.

Figure 21 (c) shows the experimental setup for the suspended nanobeam photonic crystal cavities. We used a linearly polarized tunable continuous wave (CW) laser and couple it into the tapered side of the suspended nanobeams using an objective lens with a NA of 0.7. Reflected light is collected back with a 9:1 beam splitter (BS) and then detected in a monochromator with InGaAs detector. Using this setup, we performed optical measurements for characterization of the cavities, and nonlinear optical response in the subsequent chapters.

## 4.5 Micro-photoluminescence Measurements and Cavity Characterization

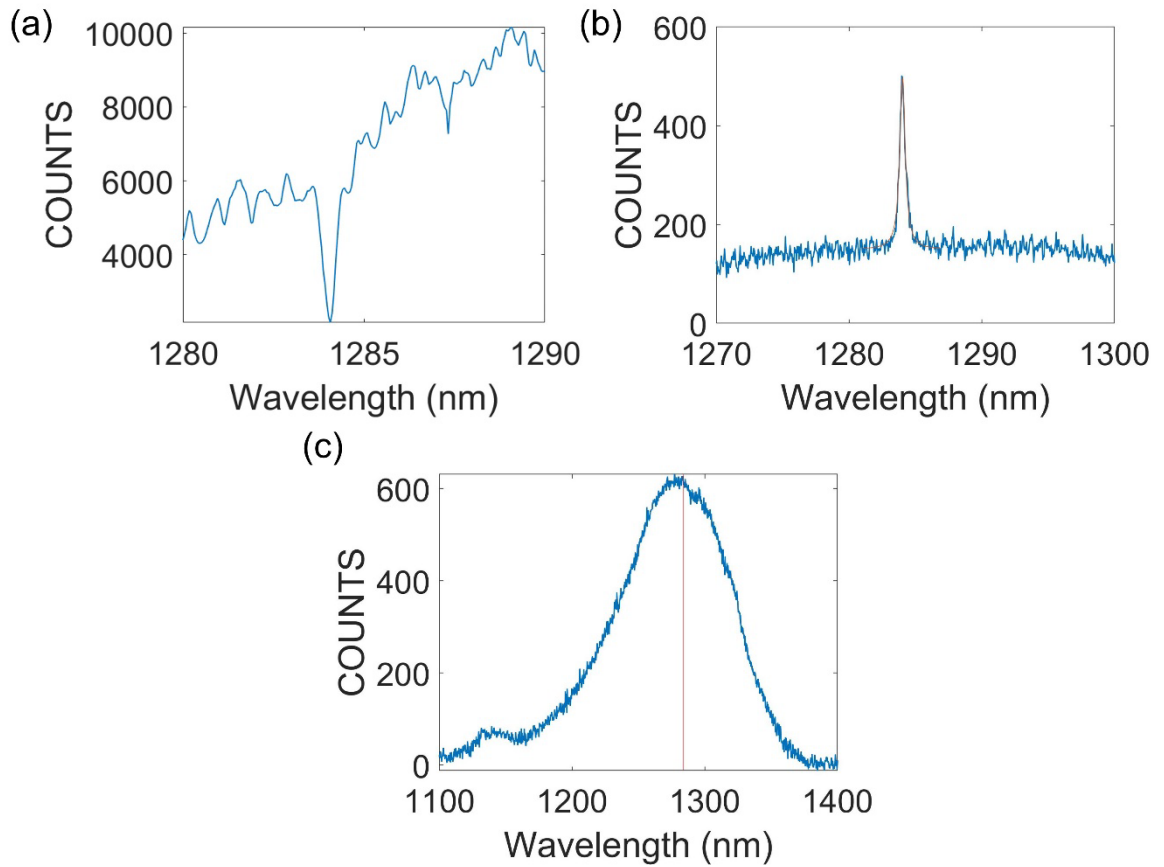


Figure 22. (a) The reflected light from the nanobeam using a broadband input laser. The cavity-dip is centered around 1284.5 nm. (b) Photoluminescence measurement using above-band 780 nm CW pump laser excitation of the nanobeam photonic crystal cavity. The cavity emission is fit to a Lorentzian curve to find the quality factor of 2830. (c) Photoluminescence measurement using above-band 780 nm CW pump laser excitation of the bare QD sample. Red line shows the position of cavity resonance on quantum dots distribution.

We used a broadband CW laser and a 780 nm above-band CW pump laser to characterize the cavity spectrum in Figure 22. Figure 22 (a) shows the cavity reflectivity spectrum when we probe the nanobeam with a broadband laser. The cavity-dip is centered around 1284.5 nm for

broadband incident power at 10nW. Figure 22 (b) shows a photoluminescence measurement from the nanobeam photonic crystal cavity using above-band excitation of the embedded quantum dot ensemble. We pumped the quantum dots with a 780 nm continuous wave laser to observe the coupling between the quantum dots and the cavity. We found the cavity quality factor to be around 2830 after fitting the cavity spectrum to a Lorentzian curve. The cavity resonance is found to be at 1284.5 nm which is same as low-power broadband reflectivity result in Fig. 22 (a). We also pumped bare the quantum dot sample with same above-band laser to understand relative position of nanobeam cavity resonance with respect to quantum dot distribution as depicted in Fig. 22 (c).

After carefully aligning optical coupling into the nanobeam cavity, we injected the CW laser off-resonantly to the nanobeam cavities to derive the coupling efficiency. Reflected light from off-resonant laser is measured before the monochromator. After taking account for efficiency of each optic on the optical path before the nanobeam taper, the coupling efficiency is calculated from ratio of total reflected and injected optical power between nanobeam cavity and the objective lens, where off-resonant reflectance from nanobeam cavity is taken to be unity from FDTD simulations [87]. From these calculations, the coupling efficiency into the nanobeam waveguide from the objective lens was found to be 30%. We attribute the difference between the measured and simulated coupling efficiency (>90%) to the angular alignment of the transferred nanobeams relative to optical axis of the objective lens, and additional the scattering losses from the outcoupling nanobeam tapers.

## 4.6 Input-Output Measurements on Cavity Reflectivity, and Thermo-optical Bistability

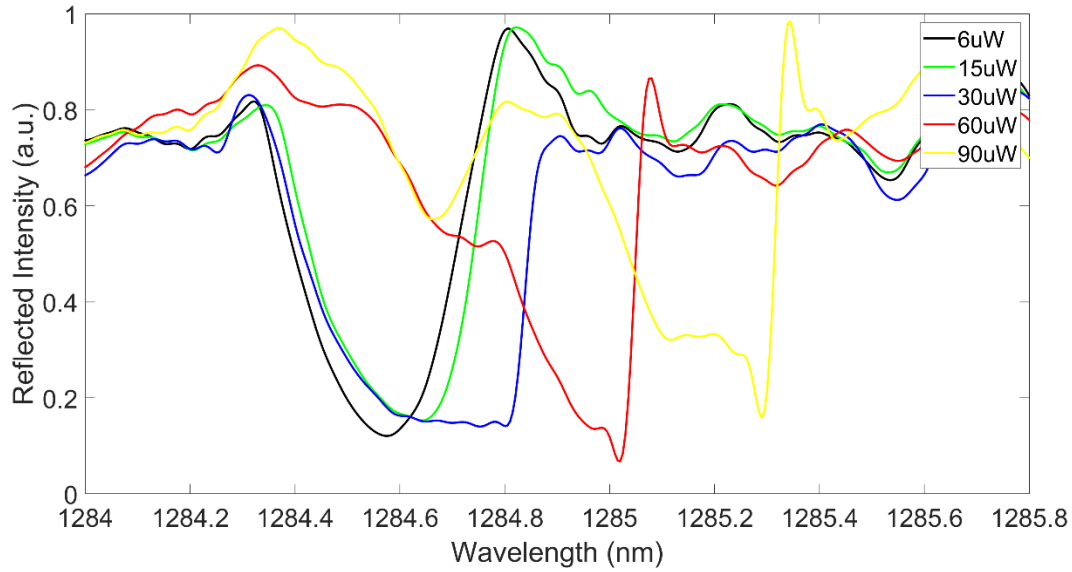


Figure 23. The reflected intensity from the cavity as the incident continuous wave laser is scanned across the cavity resonance at different power levels.

Figure 23 shows the cavity reflectivity spectrum when incident light is scanned from shorter wavelengths to longer wavelengths at various excitation powers using the continuous wave laser. For the scan at a power of  $6\text{ }\mu\text{W}$ , we see a symmetric dip of the cavity resonance at  $1284.5\text{ nm}$ , consistent with the photoluminescence spectrum of the cavity shown in Fig. 22 in the previous subchapter. When we increase the power of the incident laser to  $15\text{ }\mu\text{W}$ , we observed that the cavity resonance red shifts and becomes asymmetric. The shift increases with increasing laser power, which is a strong indication of a thermo-optic red shift due to absorption inside the cavity [72-78, 88-90]. The asymmetry in the cavity reflectivity is explained by the fact that when we scan the wavelength of the incident laser from the shorter wavelengths towards the cavity resonance, the cavity starts to absorb more light. This increased absorption causes a red shift of cavity resonance away from the laser wavelength due to thermo-optic effect. The red shift of the cavity resonance

produces a long tail towards shorter wavelengths in the reflectivity spectrum until the wavelength of the laser scan becomes resonant with the cavity and absorption reaches its maximum value. At this point, when the laser is tuned further red, the resonance with the cavity is lost and the absorption from the laser sharply decreases. As the wavelength of incident light moves away from the cavity, the cavity resonance starts to blue shift back towards the initial cavity resonance due to rapidly decreasing absorption inside the cavity. At high power levels, this sudden loss of resonance and absorption is strong enough to sharply retune the cavity back to the initial resonance and cause strong asymmetry in the reflectivity spectrum.

This result is also consistent with cavity reflectivity result in Figure 18 (a) that is numerically obtained from the theory for a simple thermo-optical cavity in the Chapter 2. The difference is that here we use a CW laser to sweep cavity reflectivity which further pushes the cavity resonance as explained before, so that asymmetric jump happens further away compared to results from Chapter 2.

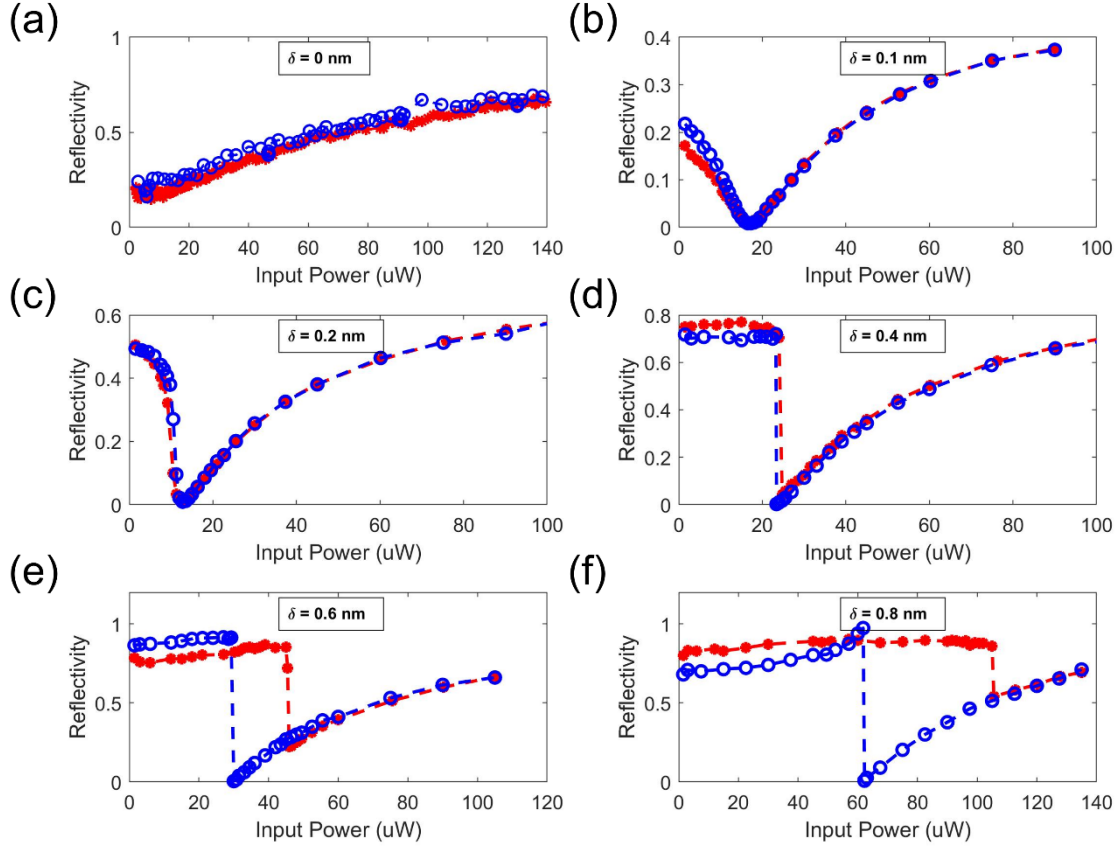


Figure 24. The cavity reflectivity for input power with different detuning  $\delta$  of wavelength of CW laser from wavelength of the cavity resonance.  $\delta = \lambda_L - \lambda_c$ , where  $\lambda_L$  is the wavelength of incident light and  $\lambda_c$  is the wavelength of the cavity resonance. The red and blue data points represent increasing and decreasing incident power, respectively. (a)  $\delta = 0$  nm. CW laser is resonant with the cavity. (b) - (f)  $\delta$  is 0.1 nm - 0.8 nm respectively. CW laser is red detuned from the cavity resonance. Input power is measured before the objective lens and adjusted according to coupling efficiency into the nanobeam waveguide.

To investigate the bistable hysteresis response of reflected light from the cavity, we set the laser wavelength at a fixed detuning of  $\delta$  from the cavity resonance, as shown in Fig. 8, and sweep the laser power. Fig. 24(a) shows the cavity reflectivity as we sweep incident laser power with  $\delta = 0$  from low to high power (red curve) and high to low power (blue curve). In the resonant ( $\delta = 0$ )

case, incident laser and cavity mode are fully overlapped, and reflected light is at the lowest reflectivity value from the cavity spectrum. As we increase the power, the cavity starts to thermooptically red shift away from the laser wavelength and the reflectivity increases slowly. In this case, we do not observe any difference between increasing and decreasing incident power.

Fig. 24(b)-(f) shows the same measurement when incident laser is further red detuned from the cavity resonance. When the  $\delta$  is below 0.4nm, we observed a strong nonlinear response without any significant difference in increasing and decreasing pump power. At 0.4 nm of  $\delta$ , we start to observe a clear discontinuity and hysteresis that corresponds to optical bistability. Theoretically, the amount of wavelength shift ( $\Delta\lambda$ ) required from the cavity resonance to reach bistable threshold has been shown to be  $\Delta\lambda = \frac{\sqrt{3}}{2} \lambda_c / Q$  [78]. For this cavity,  $\Delta\lambda$  is around 0.39 nm, which explains why hysteresis appears after 0.4 nm of  $\delta$ . Power threshold for reaching the bistable region is 23  $\mu\text{W}$  with 6.02dB response contrast between upper and lower states in the middle of hysteresis. Further increasing detuning of incident light to 0.6 nm and 0.8 nm results in a broadened hysteresis and requires a higher power threshold of 45  $\mu\text{W}$  and 107  $\mu\text{W}$  to reach the bistable region respectively. Increasing power beyond the bistable region further red shifts the cavity away from the laser. However, with less overlap between the cavity mode and the laser mode, the change in the reflectivity slows down at higher power levels.

#### 4.7 Comparison with Nanobeam Cavities without Quantum Dots

To determine whether the bistability is provided by the quantum dot absorption, we also performed similar measurements on an identical device that did not contain quantum dots. These

devices are fabricated in the same procedure with same design from a wafer that has same layered structure without quantum dots.

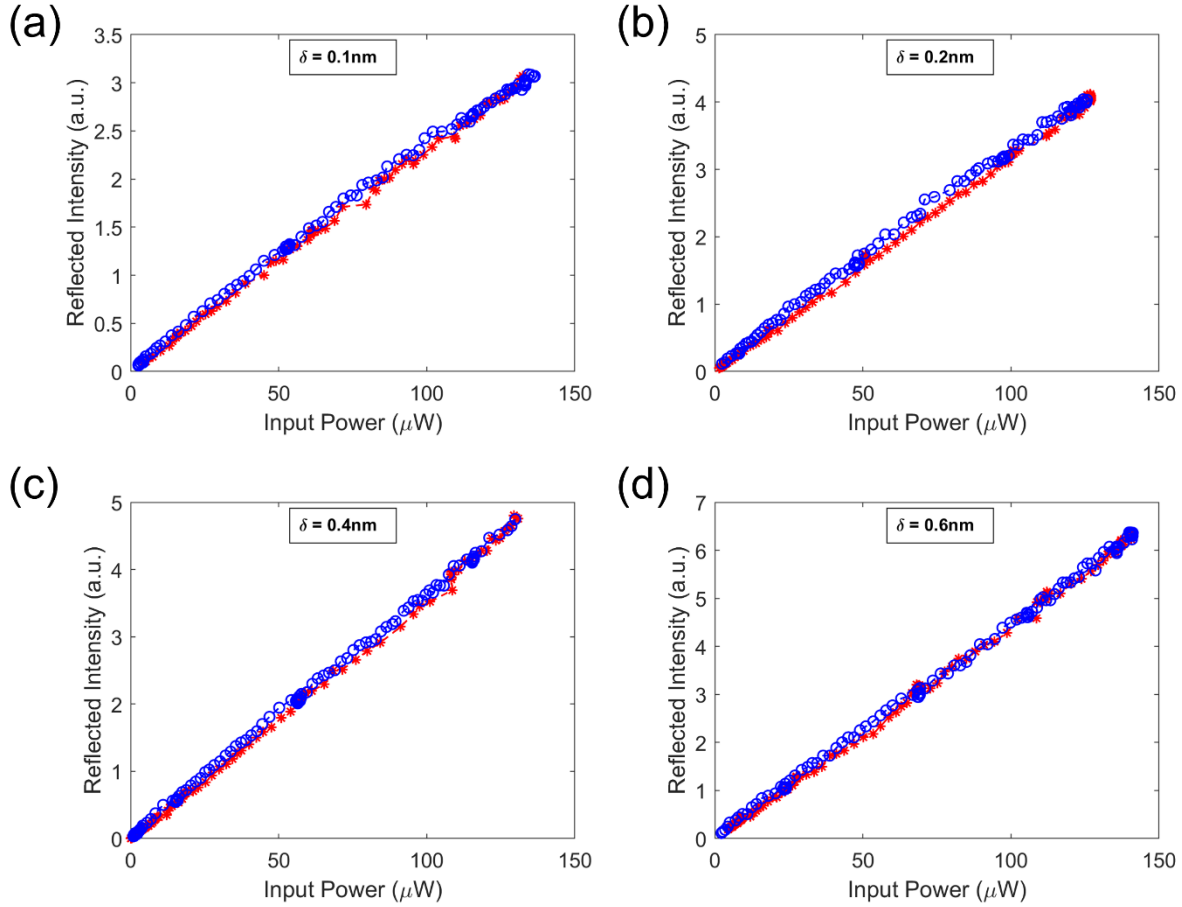


Figure 25. Input and output optical power from the nanobeam without quantum dots for different detuning  $\delta$ . The red and blue data points represent increasing and decreasing incident power, respectively. The quality factor of the cavity is around 3300.

Figure 25 shows the input and output optical power from the nanobeam without quantum dots for different detuning  $\delta$  of incident light from the cavity resonance. Power scans using resonant and detuned continuous wave lasers exhibited a linear relation, which indicates the lack of a strong thermo-optic effect in the absence of the quantum dot. In this case, we did not observe an optical

bistability, and obtained a completely linear relation between the incident and reflected power. This measurement strongly indicates that the cause of optical absorption and thermo-optic effect is due to quantum dots rather than other mechanisms such as two photon absorption in the GaAs waveguide.

## 4.8 Conclusion

In this chapter, we have worked through our results in thermo-optical bistability using quantum dots. We first started with working on a simple theory of thermo-optical cavity to understand the mechanism needed for low-power thermo-optical bistability. Then, we explained choice of quantum dots, and how that helps in achieving such low power thermo-optical bistability. Then, we have experimentally demonstrated room-temperature, thermally induced optical bistability at telecom wavelengths using quantum dots embedded in a nanobeam photonic crystal cavity. We can achieve bistable thresholds as low as 23  $\mu\text{W}$ , which is more than an order of magnitude lower than previous quantum-dot-based devices [68, 72] while having a large operation bandwidth due to the moderate quality factor of the cavity. Nanobeam photonic crystal cavity designs with high transmissions and moderate quality factors have also been demonstrated before [91-92]. These designs could be incorporated with our approach to realize air-suspended cavities that are adiabatically coupled into silicon photonic circuits using transfer-printing methods [84-86]. Moreover, the thermo-optical nature of the bistability in our device can be used to realize low-power thermal memories, and nonlinear optical activation functions [76, 93-94]. Our device is promising for many photonic applications that require hybrid-integrated low-power optical nonlinearities at telecom wavelengths.

## Chapter 5. Outlook and Future Directions

Here, we will summarize our results in this dissertation and provide future directions for next steps. In chapter 2, two methods were employed to couple quantum dot single photon sources to fiber-optics. In the first method, a nanobeam waveguide containing quantum dots, a photonic crystal mirror and a linear taper placed on top of a fiber-taper to adiabatically couple light from nanobeam taper to fiber taper. The system achieved a fiber-coupled brightness of 1.4% with  $g_2(0)$  value around 0.17 and could potentially elevate the brightness to as high as simulated value of 88% by improving the efficiency through surface treatment or employing a flame-pulled fiber. In the second method, we engineered tapered end of the nanobeam to efficiently collect light into objective lens, and couple it into the fiber. This method achieved a fiber-coupled brightness of  $9.5 \pm 0.1\%$  using above-band excitation with  $g_2(0)$  value around 0.25. While both methods provided record number brightness for telecom O-band quantum-dot based single photon sources, they are still lacking compared to NIR InAs/GaAs quantum dots. To further improve the brightness, we lastly designed and fabricated nanobeam photonic crystal cavities instead of mirrors. Different from previous fabrications, here we have tried to improve the surface quality of the InP nanobeams. We observed on average two-fold enhancement in quality factors from the nanobeam cavities due to sulfuric surface passivation and ALD capping. Moreover, we were able to switch to lensed fibers to directly couple into fiber-optics without objective lens in the second method. Future directions here would be to further improve fabrication and surface passivation recipe to realize cavity enhanced quantum dot emission efficiently coupled to fiber optics through adiabatic edge-coupling into a lensed fiber.

In the Chapter 3, we presented a platform for integrating tunable single-photon emitters on large-scale PICs. By heterogeneously integrating InAs/InP quantum dots with a cutting-edge foundry-

made silicon PIC, we have demonstrated scalable emission wavelength programmability with individual emitter resolution. Since we observed a limited spectral tuning compared to our previous results [56] and larger linewidths of quantum dot peaks, future work should consider probing quantum dot emission in each step of fabrication to deduce effect of each step on the quantum dot emission as we explained in the chapter. Moreover, to improve the scale of integration, a matrix of PDMS stamps can be considered to transfer large numbers of nanobeams photonic crystal structures in one transfer process. Once, this is done, next step of measurements could be individually tune quantum dots from each nanobeam in order to realize on-chip multi-photon interference experiments.

In the Chapter 4, we shifted our focus into producing fiber-coupled low power all-optical nonlinearities using high density InAs/GaAs quantum dots at telecom O-band. To that end, we first started with working on a simple theory of thermo-optical cavity to understand the mechanism needed for low-power thermo-optical bistability. Then, we explained choice of quantum dots and nanobeam photonic crystal cavity to produce such low power thermo-optical bistability. We achieved bistable thresholds as low as 23  $\mu$ W, which is more than an order of magnitude lower than previous quantum-dot-based devices [68, 72]. Future direction from these results could be integrating large numbers of such nanobeam cavities with silicon PICs to realize on-chip thermos-optical memories, switches and nonlinear activation functions.

## Appendices

### Appendix A. Experimental Setups for single photon collection

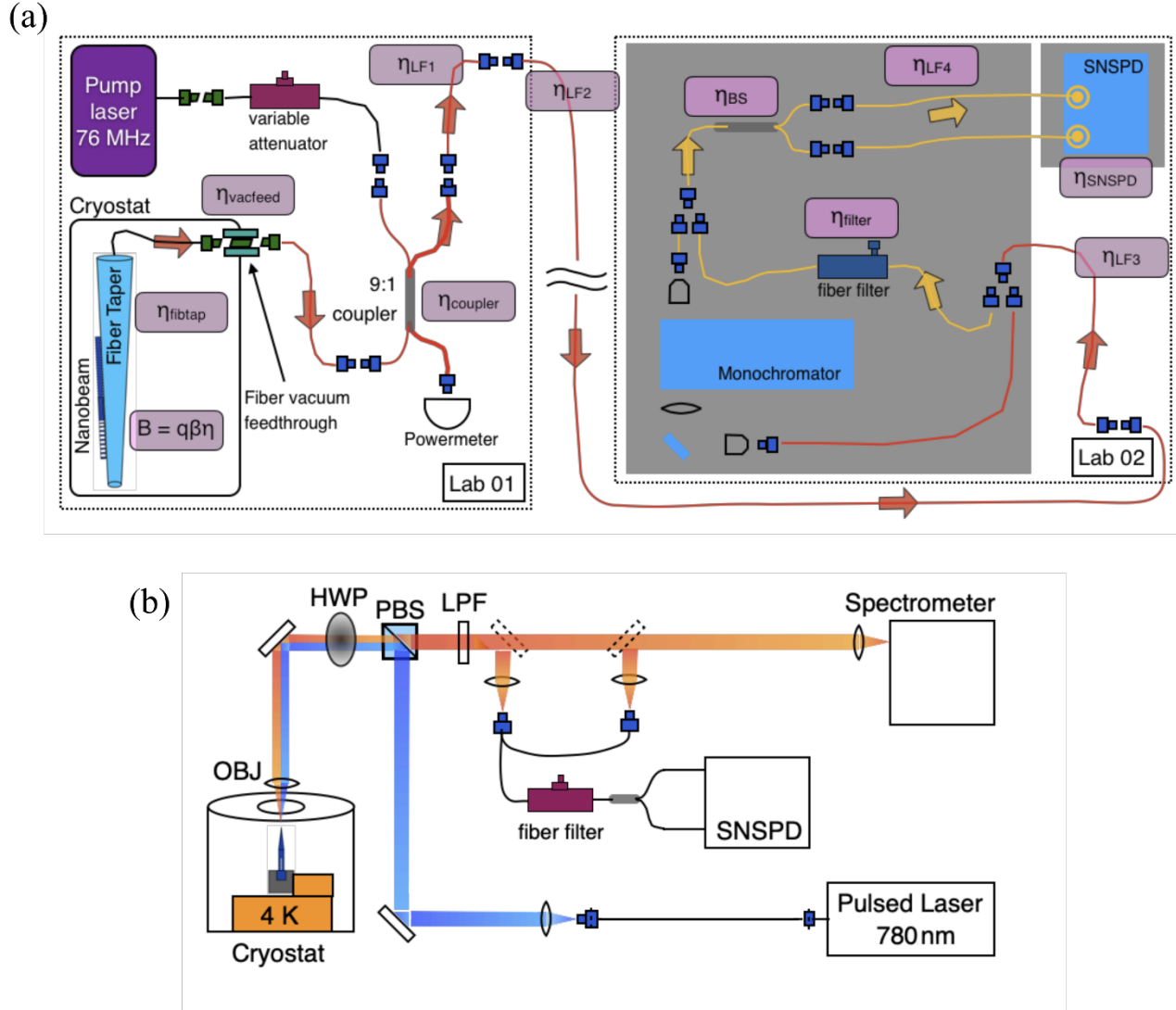


Figure 26. Experimental setups used for measurements in (a) Chapter 2.2 and (b) Chapter 2.3

Figure 26 shows the experimental setups used in chapter 2 for the fiber-coupled single photon sources. Figure 26 (a)-(b) shows the experimental setup for the Chapter 2.2 and Chapter 2.3 respectively. As explained inside these chapter, optical efficiencies for each optical components were measured to calculate total brightness into the fiber.

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