HONG OU MANDEL INTERFEROMETER: A QUANTUM MEASUREMENT TOOL

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ABSTRACT

Quantum computing research has been around for several decades, since it was first proposed by Richard Feynman. Many efforts have been made to utilize quantum systems in creation of new computing devices in the recent years. One of the essential tools used for characterization and manipulation of optical quantum systems is a Hong Ou Mandel (HOM) Interferometer. It is used in this work to provide information about propagation, distortion and degree of indistinguishability of single photons.

This work provides complete characterization of an optical tunneling effect in dielectric Bragg gratings. Samples with different thin film configurations are examined and their corresponding propagation delay times are calculated with sub-femtosecond precision. It is determined that for specific configurations for dielectric stacks, propagation delays can exhibit superluminal behavior. The distortion due to this effect is also calculated using HOM profiles.

HOM interferometer is also used to calculate the degree of coalescence between two dissimilar sources. Single photons generated by quantum dot emission and parametric down conversion are tailored through aggressive filtering techniques to be identical in their spectral, temporal and polarization profiles. The degree of their coalescence is then calculated in an attempt to create quantum interference.

This work attempts to provide better understanding of single photon interactions through use of an HOM interferometer.
To my parents, Nadejda and Constantin Borjemschi
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CHAPTER I
INTRODUCTION

1.1 Motivation

Quantum computing research has been around since 1982, when it was first proposed by Richard Feynman. It is aimed at creating devices that use the principles of quantum mechanics. Such devices have an enormous potential, as they would provide exponentially faster processing times, compared to classical computers available today. At the heart of quantum computing is manipulation, characterization, and preservation of quantum properties of various material systems. Quantum measurement is a very important part of research in the field of quantum information, because it allows the experimental assessment of various components of quantum circuitry, such as a memory, a gate, or a communication channel [1-3].

Quantum computing also offers a way to create unbreakable ciphers providing more secure communication. Since the dawn of time, people have been using code to prevent their messages from being intercepted. Some ciphers were as simple as shifting the alphabet by a designated number of letters and creating coded messages [4]. Many advances in science and mathematics made it possible to break “unbreakable” codes. With advances in computation, the ciphers also need to evolve to remain secure. Shannon et al. show that the only cipher that is impossible to break, even in principle, is Vernam cipher [3]. It is a way to encode each bit of a message with a randomly chosen key bit. This key is as long as a message itself, which posed difficulty in implementing this algorithm, since it is crucial that the key is only possessed by the sender and the recipient.
Since one of the basic principles of quantum mechanics is that it is unlikely to measure the state of a quantum system without altering it, the presence of an eavesdropper can be detected with high probability. The key of this one time pad can be sent to the recipient with very low risk of interference. This principle is at the heart of the field of quantum cryptography, or quantum key distribution [5].

In my research, I concentrate on the use of a Hong-Ou-Mandel (HOM) interferometer as a multidimensional single photon sensor. I investigate different types of quantum measurements using an HOM interferometer, in particular, propagation delay, wavepacket distortion, and degree of indistinguishability of two single photon wavepackets. All of these measurements provide essential information about single photon wavefunctions and their evolution dynamics. This research uses an HOM interferometer as a tool to determine

a) basic properties of single photons that undergo a potential barrier traversal (tunneling effect),

b) quantitatively analyze the degree of indistinguishability between photons created by different single photon sources including those of significantly dissimilar nature.

The results of this research can be used in the development of quantum computing devices.

1.2 Structure of this work

In this work, an HOM interferometer is used as a quantum sensor for single photons. I use it to time differences in propagation delays between photons, determine the amount of
distortion a photon undergoes as a result of barrier traversal, and prove indistinguishability of two photons.

The next chapter goes over the basic concepts that are used in this work. It provides information about the Hong Ou Mandel interferometer and single photon sources. Parametric down conversion (PDC) and quantum dots are examples of such sources widely used in quantum computation and described as “flying” and “stationary” qubits, respectively.

The first example shows how an HOM interferometer can be used for measuring single photon temporal delays with sub-femtosecond accuracy is described in Chapter 3. Here I use the HOM as a sensor to measure the effects of quarter wave stacks of dielectric materials on single photon propagation. Quarter wave stacks create a “potential barrier” for photon propagation, known in optics as a photonic bandgap. This type of structure has been proposed as a candidate for an optical tunneling model. Here I investigate the appropriateness of this analog. In addition, these structures have been predicted to create interesting effects due to a fast phase oscillation that takes place as a result of propagation through the quarter wave layers. I observe that very small structural changes in the structure can produce drastic changes in the time of traversal. As a result of this study, I am able to complete the analysis of the dielectric stack tunneling model.

Another capability of an HOM sensor is described in Chapter 4. Here I describe a theoretical model of an HOM interferometer. By creating a pair of correlated photons using PDC, a modulation is applied to the spectral wavefunction of the signal or idler. When the two photons are matched at a beam splitter, one observes changes in the visibility of the HOM dip
trace. This visibility is then tied to the amplitude of modulation applied to the spectral wavefunction. Symmetric and asymmetric distortions are studied.

Chapter 5 describes the current efforts of establishing entanglement between stationary and flying qubits. This effort is directed towards finding a way to bridge the connectivity gap between solid state and photonic quantum information systems, providing a valuable link for interconnecting quantum information devices of different nature. An HOM interferometer is used to determine whether one can create a heralded PDC photon and tailor it to become indistinguishable from a quantum dot emitted photon. Current progress on these efforts is reported.

Finally, Chapter 6 describes the experiment aimed to improve the results found in previous chapter by enclosing quantum dots into a micropost cavity. It reduces thermodynamically irreproducible interactions of the emitted photons and improves their coherence times. Successful fabrication of this cavity will enable the experiment in Chapter 5 to be repeated in the future with better coalescence results.
CHAPTER II
HOM INTERFEROMETER AND SINGLE PHOTON SOURCES

2.1 HOM interferometer

An HOM interferometer is based on a second-order coherence effect between the two single photon fields that are incident onto a 50/50 beamsplitter. The interferometer is based on the effect (also known as Hong, Ou and Mandel effect) that the two indistinguishable photons coalesce on a beamsplitter in such a way that the two photons would never leave the beamsplitter via separate ports. This is due to the destructive interference between the outcomes when the two photons would take separate paths as well as the Bosonic nature of light. If, however, distinguishable photons are sent through the two input ports of a beamsplitter, there will be four possible outcomes: both can be transmitted or reflected, or one can be reflected while the other is transmitted, see Fig.2.1. This effect can be observed by using two detectors, one at each output of the beamsplitter. Therefore, one will observe a coincidence count 50% of the time for the case of the two distinguishable photons and none for the indistinguishable photons [6, 7].

This effect can be explained mathematically by considering two identical photons that are in different modes $a$ and $b$ with corresponding creation and annihilation operators $\hat{a}, \hat{a}^\dagger, \hat{b},$ and $\hat{b}^\dagger$. The identical photons can then be described by

$$\hat{a}^\dagger \hat{b}^\dagger |0, 0\rangle_{ab} = |1, 1\rangle_{a,b},$$

(2.1)

where $|0\rangle$ is vacuum and $|1\rangle$ is a single photon state. When two photons meet at a beamsplitter, which is a unitary transformation, they create output states $c$ and $d$ that can be described as

$$\hat{c}^\dagger = \frac{\hat{a}^\dagger + \hat{b}^\dagger}{\sqrt{2}},$$

(2.2)
\[ \hat{d}^\dagger = \frac{\hat{a}^\dagger - \hat{b}^\dagger}{\sqrt{2}}. \]  

When two identical single photons are incident on a beamsplitter, their state can be written as

\[ |1, 1\rangle_{ab} = \hat{a}^\dagger \hat{b}^\dagger |0, 0\rangle_{ab} = \left( \frac{\hat{c}^\dagger + \hat{d}^\dagger}{\sqrt{2}} \right) \left( \frac{\hat{c}^\dagger - \hat{d}^\dagger}{\sqrt{2}} \right) |0, 0\rangle_{cd} = \frac{1}{2} (\hat{c}^\dagger \hat{c}^\dagger - \hat{d}^\dagger \hat{d}^\dagger) |0, 0\rangle_{cd} \]

\[ = \frac{1}{2} (\hat{c}^\dagger \hat{c}^\dagger - \hat{d}^\dagger \hat{d}^\dagger) |0, 0\rangle_{cd} \rightarrow |2, 0\rangle_{cd} - |0, 2\rangle_{cd}. \]  

Therefore, state \(|1, 1\rangle_{cd}\) vanishes, giving zero probability of the two identical photons being detected at different output ports of the beamsplitter [6, 7].

Single photon avalanche detectors produce an electrical pulse each time an incoming photon produces an avalanche. When the two detectors simultaneously detect one photon each, a coincidence count is recorded. If just one of the detectors clicks, no coincidence counts are recorded.

To observe a drop in coincidence counts, one needs to ensure the photons have the same wavefunction and polarization. In addition, they have to have matching spatial modes, and arrive to the beamsplitter at exactly the same time. If any of these conditions are not met, the second-order interference will not take place. Therefore, there are several ways to measure the extent of such interference by adjusting one of the parameters. For example, by inserting a delay line into the interferometer, one can adjust the pathlength of one of the photons and, thus, go from distinguishable to indistinguishable scenarios. As a result, when the pathlengths of the photons are equal, one will observe a drop in coincidence counts that approaches zero for fully indistinguishable photons. This is known as the HOM dip. This effect can also be achieved by altering polarization of one of the photons.
Figure 2.1. A schematic of HOM operation. When two distinguishable photons are sent through a beamsplitter, 4 outcomes will take place, 2 of which create coincidence counts. When the photons are indistinguishable, there will be two outcomes with zero coincidence counts.
The degree of single photon interference can be measured by the visibility of the HOM dip, which is \( \frac{C_{\text{max}} - C_{\text{min}}}{C_{\text{max}} + C_{\text{min}}} \), where \( C_{\text{max}} \) is the maximum and \( C_{\text{min}} \) is the minimum of coincidences observed. It is important to note that in practice the visibility is never exactly equal to unity. Any mismatches in the spectral function and misalignments of the setup decrease interference effects. Since most beamsplitters suffer losses and do not split the light perfectly, it is yet another reason for this imbalance.

### 2.2 Single photon sources

The ideal light source for a quantum computing system is one that emits only one photon per given time interval \( T = 1/R \), where \( R \) is the transmission rate of the source. However, most realistic light sources have a probability of emitting greater than one photon simultaneously, hindering secure communication. A single photon source has sub-Poissonian statistics, that is it has a reduced probability of emitting a photon if one has already been detected within a particular time interval. [9]

The quality of a single photon source is measured using a second-order correlation function \( g^{(2)}(\tau) \), which is defined for a classical source as

\[
g^{(2)}(\tau) = \frac{\langle I(t)I(t+\tau) \rangle}{\langle I(t) \rangle^2} = \frac{\langle E^*(t)E^*(t+\tau)E(t+\tau)E(t) \rangle}{\langle E^*(t)E(t) \rangle^2}, \tag{2.5}
\]

where \( I(t) \) is the intensity at time and \( E(t) \) is the corresponding electric field. The classical correlation function has two boundary conditions:

\[
g^{(2)}(0) \geq 1, \tag{2.6}
\]

\[
g^{(2)}(\tau) \leq g^{(2)}(0). \tag{2.7}
\]
This indicates that for a classical light source, the probability of finding a second photon is highest immediately after the first photon is detected. For a coherent source with a constant intensity, the correlation function is always equal to one, since the probability of finding a second photon is independent of the first one being detected.

In quantum mechanics, the electromagnetic field is described using creation $\hat{a}$ and annihilation $\hat{a}^\dagger$ operators and the second-order correlation function is written as

$$g^{(2)}(\tau) = \frac{\langle \hat{a}^\dagger(t)\hat{a}^\dagger(t+\tau)\hat{a}(t+\tau)\hat{a}(t) \rangle}{\langle \hat{a}^\dagger(t)\hat{a}(t) \rangle^2}.$$  

(2.8)

The only restriction on the quantum mechanical correlation function is that it cannot be negative. It no longer follows Poissonian statistics. Quantum photon sources can violate both conditions 2.6 and 2.7, meaning there can be a source for which the probability of detecting a second photon is lowest immediately after the first one is detected. Such a source is antibunched and is considered a true single photon source when second photon detection probability reaches zero [10].

The first experimental observation of the antibunching effect was recorded by Kimble et al. [10]. This was done by exciting a thermal beam of sodium atoms with a dye laser. The laser was stabilized in frequency and intensity and tuned to match an effective two-level transition. They then collected the emitted fluorescent light at right angles to the laser and atomic beams using an optical objective that projects a 100 micron regions onto an aperture. The light is then sent through a 50/50 beamsplitter and detected by the photomultiplier tubes. The sodium atom beam is also divided by a beamsplitter and monitored to ensure that no more than one or two atoms can contribute to the observed fluorescence at the same time. When a sodium atom emits
a photon, a short amount of time has to pass before it is re-excited and another photon can be emitted. Therefore, the second-order correlation function vanishes at time zero.

Antibunching from fluorescence has also been shown in organic molecules, such as a single pentacene molecule in a p-terphenyl crystal by Basché et al. [11]. The researchers pumped the lowest zero-phonon transition and detected fluorescence for the first excited state. By using two detectors to start and stop the measurement, they clearly observed antibunching. However, the lifetimes of these vibrational states are very short, on picosecond scale, making integration of these systems into a quantum computer very unlikely. In addition, both sodium atoms and organic molecules suffer from a photobleaching effect, that is after a certain period of time they stop emitting photons altogether.

Using nitrogen vacancy (NV) centers in synthetic diamond crystals solved the problem of photobleaching in single photon sources. NV center is a defect in diamond’s crystaline structure that can be created with a reasonable degree of control through electron irradiation and high temperature annealing in vacuum [12]. Gruber et al. used 100 micron thick diamond samples. By irradiating them at $10^{12}$ electrons/cm$^2$ for one hour, they were able to yield defect concentrations of 0.2 to 200 centers per cubic micrometer. This density is low enough to allow for individual defects to be isolated and investigated. The samples are excited and probed with an optical microscope to detect the density of the resultant defects. There is a direct correlation between the irradiation dose during NV center formation process and the resultant fluorescence intensities. With very low doses the intensity drops, however, the spacing between them increases and areas of single defects can be located. Gruber et al. found that an ensemble of NV
centers (around 10 defects) showed a 10% decrease in fluorescence intensity and 15% decrease for different NV centers. [12]

While diamond NV centers offer a solution to photobleaching effects, the light emitted by these defects is largely broadband. It is also not a largely used semiconductor material due to its cost, making integration of NV centers of diamond into main stream devices impractical. Parametric down conversion and quantum dots are methods used in optical and semiconductor technologies, respectively, to reliably produce single photons and are used in this work.

### 2.3 Spontaneous Parametric Down Conversion

One of the major and most established techniques to create single photons is spontaneous parametric downconversion (SPDC), which is a second order nonlinear optics effect. Polarization $\mathbf{P}$ of any material is a function of the electric field $\mathbf{E}$ that can be described as

$$\mathbf{P}(t) = \chi^{(1)} \mathbf{E}(t) + \chi^{(2)} \mathbf{E}(t) + \chi^{(3)} \mathbf{E}(t) + \ldots$$  \hspace{1cm} (2.9)

If a material has a nonzero second order component of the polarization function, it can give rise to Second Harmonic Generation, an effect first observed by Franken et al. They propagated a ruby laser (694 nm) through a quartz sample and observed at the output the beam of the same frequency as well as ultraviolet radiation at double the original frequency [13].

The SPDC process is very similar to second harmonic generation operating in reverse. A nonlinear crystal is used to “split” a pump photon into two photons of lower frequency [7]. For historical reasons, these two photons are called signal and idler. The propagation vector of these photons can be collinear with the pump laser (collinear SPDC) or have some angle $\theta$
(noncollinear SPDC). Since the process itself does not change the state of the crystal, both energy and momentum must be conserved,

$$\vec{\omega}_{\text{pump}} = \vec{\omega}_s + \vec{\omega}_l,$$

(2.10)

where $\omega_{\text{pump}}$, $\omega_s$, and $\omega_l$ are frequencies of the pump, signal and idler photons, respectively. The gain of SPDC process is calculated to be

$$g = [g_0^2 - (\Delta k)^2]^{1/2},$$

(2.11)

where $g_0$ is the maximal possible gain and $\Delta k$ is a phase mismatch. Optimal conditions for SPDC process are achieved when phase mismatch is minimized or

$$\Delta k = k_s + k_l - k_{\text{pump}} = 0.$$  

(2.12)

![Figure 2.2. Non-collinear SPDC schematic. One pump photon is split into a signal and idler of lower frequency. Energy and momentum are conserved in the process.](image)

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Given the spectral features of the signal and its location, one can accurately predict the spectral composition of the idler and its location. Having two photons makes heralding possible, because presence of a signal photon indicates the existence of an idler [7]. SPDC is not a true single photon source since it is not antibunched. However, when one of the photons is heralded, it then exhibits single photon characteristics.

As mentioned above, in SPDC process the momentum has to be conserved together with energy conservation. Thus, the phase matching condition $k_3 = m_1 \cdot k_1 + m_2 \cdot k_2$, where $k_{1,2,3}$ are wave vectors, is satisfied. Given the laws of dispersion, this is not a trivial task. There are a few ways to achieve phase-matching at a desired wavelength. Typically, a birefringent crystal is used, where the refractive index depends on the polarization and direction of the pump light. The crystal has three axes and birefringence indicates that one or two of the axes can have different index of refraction. By adjusting the angle and polarization of the incoming light, one can satisfy the phase-matching condition. In type I phase-matching the signal and idler photons have the same polarization that is perpendicular to that of the pump photon. In type II phase-matching the signal and idler photons have perpendicular polarizations. In this research, both type I and type II phase-matching will be used. A schematic of non-collinear SPDC is shown in Figure 2.2. [13]

For the first part of my research I use a LiIO3 crystal to generate non-collinear type I SPDC. A wide spectral range of single photons of parallel polarizations were created. The photons with identical spectra were then selected using filtering and single-mode coupling, see Chapter 3. For the second part of the experiment, I use a periodically poled KTP crystal in a
type II collinear geometry, see Chapter 5. To obtain the phasematching at the correct wavelengths of the signal and idler, this crystal has to be temperature tuned.

### 2.4 Quantum Dot

Single photons can also be generated by quantum dots in a process of recombination. Quantum dots are semiconductor implementations of the “particle in the box” problem of quantum mechanics. To create a potential well, a thin layer of semiconductor material with lower bandgap energy is placed between layers of dielectric Bragg reflector (DBR) stacks with higher bandgap energy. The thickness of the semiconductor layer affects the properties of carriers. At low temperatures, all carriers occupy the lowest energy state and are free to move within the well. As the number of dimensions decreases, the density of states profile becomes more singular. It becomes fully quantized for a quantum dot, with the number of dimensions equal to zero.

Due to this behavior of the carriers in a quantum dot, it is considered an artificial atom and the antibunching fluorescence experiments can be implemented with them. To produce electron hole pairs, laser light with energy equal to (resonant excitation) or higher than (above band excitation) the bandgap of the material is used. In the above band excitation these carriers then diffuse towards the quantum dots and are trapped there, relaxing to the lowest energy state. In the resonant excitation the electrons and holes are formed inside the dot itself. A photon is emitted during recombination process and is collected by optical means inside a cryostat [14].

The quantum dot samples used in this research are grown at a Stanford University facility. The samples are fabricated using molecular-beam epitaxy by capping (001) GaAs
Figure 2.3. InAs/GaAs quantum dot transition diagram. Above band excitation is used to trap carriers and relax them into the lowest energy state. During recombination process, a photon is emitted and is collected by an optical fiber.
substrate with 75 nm of InAs. The quantum dot self-assembly process takes place when high temperatures are applied to the sample. Higher temperatures increase the intermixing between InAs and GaAs and shorten the quantum dot emission wavelength. Using electron-beam lithography and dry etching, mesas of 120 nm tall, 200 nm wide, and 50 µm apart are formed. This process was optimized for low QD density fabrication, such that each mesa contains no more than one QD structure [8].

Semiconductor quantum dots are promising candidates for nanoscale quantum applications. They have very narrow optical bandwidths and a large photon flux. They are also very robust and have the potential for large scale manufacturing, which makes them an attractive substitute for alkali atoms and ions in quantum processing.

2.5 The Basic Principles of Micropost Cavities

When dealing with spontaneous emission of the quantum dot in the experiment described in Chapter 5, it is crucial to collect as much of the emitted light as possible. This can be done by using nonlinear optical components that improve collection and direct propagation of the single photons. However, that is difficult to implement due to the size of the devices in question. Such interactions also alter the statistical behavior of photons. By placing quantum dots inside a cavity and reducing the interaction of its dipole and electromagnetic vacuum, the emission itself can be improved. This is known as Purcell effect or cavity quantum electrodynamics (QED) in a weak coupling regime [15].

Field quantization is used to describe emission of a photon by a quantum dot. There is a non-zero energy present even when no photons are emitted, also called a vacuum state. The
existence of this energy is attributed to the presence of virtual photons. They, in turn, spontaneously stimulate a quantum dot in the same way a real photon triggers stimulated emission. When a quantum dot is placed inside a cavity, the statistical behavior of virtual photons is altered. If the cavity is resonant with the atomic transition of a quantum dot, the vacuum field is enhanced, creating higher probability of spontaneous emission. On the other hand, if the cavity is not resonant with the atomic transition, the vacuum field is reduced and so is the probability of photon emission. [8, 14]

Micropost cavities for quantum dots are mathematically described using Jaynes-Cummins model for a two level atom placed in a cavity resonant with the atomic transition at frequency $\omega$. The model assumes the atom is placed at the antinode of the standing wave formed by the cavity and its dipole moment is parallel to the electric field with infinite lifetime and linewidth of zero. The Hamiltonian for this system is then written as

$$\hat{H} = \hbar \omega (\hat{a}^\dagger \hat{a} + \hat{n}^\dagger \hat{n}) + \hbar g (\hat{a}^\dagger \hat{n} + \hat{n}^\dagger \hat{a}),$$

(2.13)

where $\hat{a}$ is the annihilation operator and $\hat{\pi} = |g\rangle\langle e|$ is the operator that takes an atom from the excited state to ground state. The Rabi frequency $g$ is in turn given by

$$g = \frac{eD}{\hbar} \sqrt{\frac{2\hbar \omega}{V_0}},$$

(2.14)

with $D$, the dipole moment and $V_0$, the physical volume of the cavity. Rabi frequency is an important factor in describing the system. It indicates the frequency the atomic state alternates between having one photon in the cavity while in a ground state and having no photons in the cavity while in excited state. [14]

The resultant equations of motion are described as follows:
\[
\frac{d}{dt} \hat{\sigma}_e = ig(\hat{a}^\dagger \hat{n} - \hat{n}^\dagger \hat{a}),
\]
\[
(2.15)
\]
\[
\frac{d}{dt} \hat{\sigma}_g = -ig(\hat{a}^\dagger \hat{n} - \hat{n}^\dagger \hat{a}),
\]
\[
(2.16)
\]
\[
\frac{d}{dt} \hat{n} = ig(\hat{\sigma}_e - \hat{\sigma}_g)\hat{a},
\]
\[
(2.17)
\]
\[
\frac{d}{dt} \hat{a} = ig\hat{n},
\]
\[
(2.18)
\]

where \(\hat{\sigma}_e = |e\rangle\langle e|\) and \(\hat{\sigma}_g = |g\rangle\langle g|\) are population operators.

When calculating the improvement of optical emission due to an optical cavity versus signal collected in free space, damping parameters have to be introduced to equation 2.17. Quality factor \(Q\) and fluctuation operator \(\hat{F}(t)\) help describe a more physical cavity with field decay. Equation 2.18 is rewritten as

\[
\frac{d}{dt} \hat{a} = -\frac{\omega}{2Q} \hat{a} - ig\hat{n} + \hat{F}(t).
\]
\[
(2.19)
\]

The ratio of emission rate in a cavity to the emission rate in free space is then given by

\[
\frac{\gamma}{\gamma_0} = \frac{3Q\lambda^3}{4\pi^2V_0},
\]
\[
(2.20)
\]

where \(\lambda\) is wavelength of the quantum dot emission. This factor is also known as the Purcell factor and it is widely used to describe optical cavities in QED [15]. A more detailed derivation of these results can be found in reference [16].
2.6 Summary

This chapter describes general principles behind the concepts used in the scope of this work. Hong Ou Mandel interferometer is a necessary tool to perform many measurements in the field of quantum optics. It is very versatile and provides several dimensions of information about quantum systems.

Single photon sources are another crucial component of quantum optical experiments. Several types of sources are described in this Chapter with emphasis on parametric down converted sources and quantum dots.
CHAPTER III
PROPAGATION THROUGH QUARTER WAVE DIELECTRIC STACKS.

3.1 Introduction

Dielectric stacks are series of dielectric thin film layers deposited on top of one another. Dielectric stacks with periodic quarter-wave thick layers give rise to photonic bandgaps that serve as dielectric mirrors and are frequently compared to tunneling potential barriers for photons. Particularly, as in the case of canonical potential barriers in quantum mechanics, theoretical models of photon traversal through quarter-wave dielectric stack barriers that arise due to Bragg reflection predict the saturation of the propagation time with the barrier length, a remarkable result. This saturation is known as the Hartman effect [18] (see Ch. 1), which predicts an increase in apparent traversal velocities with increase in thickness of a barrier. As a result, the transit time of photons traveling through these photonic bandgap barriers has been shown to be apparently superluminal under some conditions [19]. That is, the position of an exiting, much-attenuated, light pulse is found ahead of that of a reference pulse transiting a similar region of vacuum.

Interestingly, the opaque barrier model has been researched in the past as an alternative to tunneling, where the mathematical analogy between the evanescent light propagation and the Schrödinger equation governing the 1D motion of a quantum particle is exploited [19]. Later, it was pointed out [20], that a model based on bandgap properties of a dielectric quarter-wave-stack is equivalent to quantum mechanical tunneling, but only if a slow varying envelope approximation (SVEA) is applied. In general, the SVEA simplifies theoretical treatment of wave phenomena by removing the fast oscillating optical phase, and can adequately describe the
propagation only if the complex amplitude (that serves as both the envelope and a variation of the phase) changes slowly and continuously. In this case, SVEA replaces the underlying physical process – the interference between two counter-propagating waves reflected off of the boundaries of dielectric layers by a single equation that is mathematically equivalent to one describing an evanescent field. The key difference between the underlying process and its SVEA treatment is that both interfering waves are oscillatory, while a true evanescent wave is not.

The original prediction of Hartman indicates that the asymptotic saturation of the transit time for an opaque barrier is smooth, however it has been shown that for non-evanescent barriers such as dielectric stacks this is no longer true. Small changes in a dielectric stack, which can alter the details of the corresponding bandgap properties, have been predicted to cause rather dramatic variations in the transit time. For alternating high and low index quarter-wave dielectric stacks the addition of single layers causes an alternation; the transit time saturating to different values for even and odd numbers of layers [21, 22, 23]. A simple example where a minor modification to a stack could substantially change the transit time would be where a dielectric stack is simply reversed and built onto a substrate. Time-reversal symmetry would require the transit in each direction through the isolated stack be the same, however, a substrate layer breaks the symmetry, and simply reversing the stack ordering from the substrate can produce a substantial change in the transit time. I emphasize that upon reflection, the phases of the counter-propagating waves experience jumps that are incompatible with the SVEA. Indeed, theoretical calculations with no approximations applied show that if the structure of dielectric stacks is slightly altered, the propagation times may be significantly changed [22]. Therefore, while [19] indeed demonstrates an apparent superluminality of traversal qualitatively, it does not establish a quantitative estimate
for delay times in particle-barrier experiments, hence other optical models of tunneling should be used.

I observe these effects and demonstrate that by adding a single layer to a 30-layer stack I am able to increase or decrease the measured transit times by more than five times the transit time across the added layer if it was in isolation.

### 3.2 Previous work

Steinberg, et al., [19] was the first to measure the transit times of single-photons through a dielectric stack and observed apparently “superluminal” propagation delay times. In the experiment, Steinberg uses a KDP crystal pumped with 351 nm laser to create twin photons through parametric down conversion (PDC). By selecting identical photons at 702 nm and sending them through a Hong-Ou-Mandel (HOM) interferometer, he is able to determine how the dielectric stacks affect the propagation delay difference of the two photons. As a result, he found that the used stack configuration caused the photon to propagate with seemingly superluminal velocity, arriving 1.47 fs before the photon traveling the same distance in air. His experiment points out the usefulness and some of the limitations of studying such optical bandgap structures as an analogy to particle tunneling through a classically-opaque barrier. The single-particle nature of the photons used to probe the structure suggests the analogy with particle transit times and makes wave-interference explanations difficult to accept at face value, as discussing “which part of the wavepacket gets through” is meaningless for a single particle detection. The measurement is based on a postselection of a set of successful tunneling events and can be viewed as a “weak measurement” [24]. The fact that even a single photon can be
described as an electromagnetic pulse, however, means that a wave picture is valid. All of the conflicting explanations and pictures for such superluminal behavior have added to the interest that such experiments hold for the community studying quantum physics, classical analogies, and fundamental physical phenomena.

While the work of Ref. [19] tested for wavepacket distortion and pulse reshaping, the limits put on such reshaping were not strong, and it is pointed out in Ref. [23] that only very subtle distortions in the transmitted wavepacket or wavefunction are required to obtain the appearance of superluminal effects. If the incident pulse is a Gaussian wavepacket and the “reshaped” (delayed or advanced) pulse is Gaussian as well, then they will be impossible to distinguish in an interferometer. The evidence of distortion in the transmitted pulse or wavefunction may be hard to detect; if it looks enough like the reference pulse, an interferometer cannot, for instance, tell one Gaussian from another. The distortion of the wavepacket is discussed further in Ch. 4.

Transit time measurements through a series of dielectric stacks have also been performed by Spielmann et al., [25] using femtosecond laser pulses. These authors report that the transit time became monotonically independent of the barrier thickness as the barrier becomes more varied only by adding more high- and low-index layers in pairs. As has been pointed out since then, the transit time is not expected to saturate monotonically if, instead, layers are added to the stack one at a time [21, 22, 23]. This is the effect that I investigate here.

In the case of Ref. [25] the optical bandgaps are made much more opaque than in [19] and the event rate was kept up by having many photons in each pulse. In this case the pulse bandwidth was also large enough to observe some obvious pulse distortion. Pulse narrowing
resulted, from a spectral point of view, from the transmission variation of the bandgap over the spectrum of the pulse; suppressing the center frequencies and effectively broadening the spectrum of the transmitted pulse.

More recently, measurements on 1-D optical bandgap structures have been made using fiber Bragg gratings as the tunneling barrier [26]. As the barrier length, or reflectivity, went up the apparent velocity became more and more superluminal, demonstrating the Hartman effect and its smooth saturation for such Bragg grating barriers. Very little pulse distortion is reported even with significant pulse advances under these conditions. While no study is made of the pulse delay as individual periods of the grating were added, more general measurements as a function of barrier thickness indicated the appropriateness of a Hartmann-type saturation.

3.3 Quarter-wave dielectric stacks

I study single photon traversal in stop bands of 1D Bragg gratings made of alternating quarter wave layers of higher (H) and lower (L) refractive index dielectrics deposited onto a glass substrate. There are two types of stacks with an even number of layers, $2N$, represented as $(HL)^N$ and $(LH)^N$. For an odd number of layers $2N +1$, one has two more types of stacks: $(HL)^NH$ and $(LH)^NL$, Fig. 3.1.

These types of structures are used extensively as mirrors as with higher number of layers most very high reflectance can be produced, Fig. 3.2. Here of particular interest are the effects of structural effects on the propagation delay that takes place. Specifically, I investigate whether this type of structures can be used as an appropriate model of tunneling.
3.4 Theoretical predictions

It was initially suggested [7], and it has been shown [27], that a HOM interferometer measures propagation time delays that correspond to group delays in forbidden gap traversal experiments. The theoretical treatments of structures used (which is similar to [21, 22]) shows that different structures yield very different traversal times. It turns out that all four structures (if considered separately) exhibit Hartman-like saturation, as seen later in this section. Because I consider a stack grown on a glass substrate, the two even layer structures \((HL)^N\) and \((LH)^N\) cannot be considered to be equivalent, since the substrate breaks the symmetry here.

To model these structures, I start by considering a single layer of a dielectric stack. I consider a dielectric layer of a quarter wave thickness deposited on the surface of a substrate. A diagram of the linearly polarized wave traveling through the structure is depicted in Fig. 3.3. Here each wave \(E_{\text{il}}, E_{\text{rll}},\) and so forth, are composite of all fields moving in that direction at that point. Therefore, the coherent summation of multiple waves is already built into the definition of these fields. The tangential components of the fields have to be continuous throughout the structure, and, thus, they have to be equal at the boundaries. At the first boundary, using the expression \(\vec{H} = \sqrt{\frac{\varepsilon_0}{\mu_0}} n \vec{k} \times \vec{E},\) I set

\[
E_i = E_{\text{il}} + E_{\text{rl}} = E_{\text{il}} + E'_{\text{rll}},
\]

(3.1)

and

\[
H_i = \sqrt{\frac{\varepsilon_0}{\mu_0}} (E_{\text{il}} - E_{\text{rl}}) n_0 \cos \theta_{\text{il}} = \sqrt{\frac{\varepsilon_0}{\mu_0}} (E_{\text{il}} - E'_{\text{rll}}) n_i \cos \theta_{\text{il}},
\]

(3.2)

where \(n_0, n_i,\) and \(n_S\) are refractive indeces of air, stack, and substrate, respectively.
Figure 3.1. Four types of structures used for the experiment. Different combinations of starting and ending layers of thin films have great influence on propagation delays.
Figure 3.2. Light propagation through a quarter-wave dielectric stack. Refraction has been omitted for simplicity.
Similarly, at the second boundary

\[ E_{ll} = E_{lII} + E_{rl} = E_{rII} \quad (3.3) \]

and

\[ H_{ll} = \sqrt{\frac{\varepsilon_0}{\mu_0}} (E_{lII} - E_{rII}) n_i \cos \theta_{lII} = \sqrt{\frac{\varepsilon_0}{\mu_0}} E_{ll} n_S \cos \theta_{lII} \quad (3.4) \]

A wave that traverses through a single layer of the dielectric stack will also undergo a phase shift of

\[ \Lambda = 2n_i d \cos \theta, \text{ or } k_0 h, \] where \( k_0 = \frac{2\pi}{\lambda_0} \) and \( h = \frac{\lambda_0}{4} \) is the thickness of a single stack. Then,

\[ E_{lII} = E_{d} e^{-ik_0 h} \quad \text{and} \quad E_{rII} = E'_{rII} e^{ik_0 h}. \quad (3.5) \]

Using Eq. 3.5, one can rewrite Eqs. 3.3 & 3.4 as

\[ E_{ll} = E_{d} e^{-ik_0 h} + E'_{rII} e^{ik_0 h} \quad \text{and} \quad H_{ll} = (E_{d} e^{-ik_0 h} - E'_{rII} e^{ik_0 h}) \sqrt{\frac{\varepsilon_0}{\mu_0}} n_i \cos \theta_{lII}. \quad (3.6) \]

Using these equations, one can now solve for \( E_{dl} \) and \( E'_{rII} \), where

\[ E_{dl} = \frac{\sqrt{2}}{2} e^{ik_0 h} (E_{ll} + \sqrt{\frac{\mu_0}{\varepsilon_0}} \frac{1}{n_i \cos \theta_{lII}} H_{ll}) \quad (3.7) \]

and

\[ E'_{rII} = \frac{\sqrt{2}}{2} e^{-ik_0 h} (E_{ll} - \sqrt{\frac{\mu_0}{\varepsilon_0}} \frac{1}{n_i \cos \theta_{lII}} H_{ll}). \quad (3.8) \]

By substituting Eqs. 3.7 and 3.8 into Eqs. 3.1 and 3.2 and defining \( Y_i \equiv \sqrt{\frac{\varepsilon_0}{\mu_0}} n_i \cos \theta_{lII} \), one can arrive at the following expressions for \( E_i \) and \( H_i \):

\[ E_i = E_{ll} \cos k_0 h + H_{ll} (i \sin k_0 h)/Y_i \quad \text{and} \quad H_i = E_{ll} Y_i \sin k_0 h + H_{ll} \cos k_0 h. \quad (3.9) \]
Figure 3.3. A schematic representation of the electric and magnetic fields at the boundaries of a single quarter-wave dielectric stack.
Equation (3.9) above can also be written in matrix notation in the following manner:

\[
\begin{bmatrix}
E_I \\
H_I
\end{bmatrix} = \begin{bmatrix}
\cos k_0 h & (i \sin k_0 h) / Y_i \\
Y_i i \sin k_0 h & \cos k_0 h
\end{bmatrix}
\begin{bmatrix}
E_{II} \\
H_{II}
\end{bmatrix} = M_1 \begin{bmatrix}
E_{II} \\
H_{II}
\end{bmatrix}, \quad (3.10)
\]

where \( M_1 \) is the characteristic matrix of a single dielectric layer, which can be used to describe the permutation on the incident field that takes place as a result of propagation through the structure. Since \( M_1 \) ensures continuity at the boundaries, if a second layer of dielectric material is deposited, creating a third boundary, one can simply multiply two characteristic matrices together to create a matrix appropriate to describe the entire structure. For a structure of \( 2N \) layers, one can characterize the system by

\[
\begin{bmatrix}
E_I \\
H_I
\end{bmatrix} = M_1 M_2 M_3 \cdots M_{2N} \begin{bmatrix}
E_{II} \\
H_{II}
\end{bmatrix}. \quad (3.11)
\]

For any given stack system, one can use the above equation to calculate a characteristic matrix for the specific values of \( h \) and \( k_0 \), where \( M = \begin{bmatrix} m_{11} & m_{12} \\
m_{21} & m_{22} \end{bmatrix} \). In this case the first boundary is the air-stack interface and the last boundary is the stack-substrate interface. Therefore, one can write

\[
Y_0 = \sqrt{\frac{\varepsilon_0 \mu_0}{\mu_0}} n_0 \cos \theta \quad \text{and} \quad Y_S = \sqrt{\frac{\varepsilon_0 \mu_0}{\mu_0}} n_S \cos \theta. \quad (3.12)
\]

One can now expand the expressions for \( E_I, E_{II}, H_I \) and \( H_{II} \) from Eqs. 3.1-3.4 and write Eq. 3.10 in the following manner:

\[
\begin{bmatrix}
E_{II} + E_{II} \\
(E_{II} - E_{II}) Y_0
\end{bmatrix} = M \begin{bmatrix}
E_{II} \\
E_{II} Y_S
\end{bmatrix}. \quad (3.13)
\]
Since reflectivity and transmissivity are defined as \( r = \frac{E_{i1}}{E_{il}} \) and \( t = \frac{E_{il}}{E_{i1}} \), Eq. 3.13 can be expanded and solved for \( r \) and \( t \). As a result, one arrives at the following expressions for reflectivity and transmissivity of the dielectric stack structures:

\[
\begin{align*}
    r &= \frac{Y_0 m_{11} + Y_0 Y_s m_{12} - m_{21} - Y_s m_{22}}{Y_0 m_{11} + Y_0 Y_s m_{12} + m_{21} + Y_s m_{22}} \quad (3.14) \\
    t &= \frac{2Y_0}{Y_0 m_{11} + Y_0 Y_s m_{12} + m_{21} + Y_s m_{22}} . \quad (3.15)
\end{align*}
\]

The phase change in the photon wavefunction \( \phi \) can then be calculated by taking the argument of transmissivity. Finally, phase time \( \tau \) can be calculated, where \( \tau = \frac{\delta \phi}{\delta \omega} \).

For more information about this calculation, see Ref. [28].

Using the principles described above, I use Mathematica to model quarter-wave stack structures. The results of the modeling can be seen in Figs. 3.4 and 3.5 for the stack refractive indices of 2.19 and 1.97 for H and L layers, respectively, and the wavelength of 702 nm. Transmission and propagation delay for each stack differs significantly. Each structure produced its own propagation delay branch with distinct saturation values. The lowest and highest saturation points are separated by roughly 15 femtoseconds.

Hartman saturation can only be observed by adding layers to any given structure two at a time. However, if layers are added one at a time, jumps in the propagation delay times occur. In particular, for the \((LH)^N L\) structure, the saturation time is significantly higher than for the \((HL)^N H\) structure. If any of these odd layer structures is changed by adding one more layer, yielding \((LH)^{N+1}\) and \((HL)^{N+1}\) respectively, the traversal time abruptly changes, as is evident in Fig. 3.8. In fact, addition of single layers will cause the transmission and propagation delay to
Figure 3.4. a) Theoretical plot of transmission dependency on wavelength for the four types of dielectric stack structures. Photonic bandgaps can be seen for each of the stack structures. b) Theoretical plot of transmission at 702 nm wavelength as a function of the number of bilayers for the four different types of stack structures.
Figure 3.5. Propagation delay plot for the four stack structures. Each branch exhibits Hartman saturation effects, with different saturation points for each branch.
oscillate between the branches specific for the stack structures. *Adding* an extra layer to the \((\text{LH})^N\text{L}\) structure produces a \((\text{LH})^{N+1}\) structure which would surprisingly *decrease* the propagation delay, while *adding* an extra layer to the \((\text{HL})^N\text{H}\) structure produces \((\text{HL})^{N+1}\) structure which would *increase* the propagation delay. This phenomenon contradicts the slowly varying envelope approximation, which predicts equal propagation delays for the structures with equal optical thickness.

### 3.5 Sample

The difference between the saturation values of the traversal times (i.e. when \(N \to \infty\)), Fig. 3.5, is proportional to the geometric average index of refraction of the two layers and is inversely proportional to its difference [22, 29]. Hence, to maximize the effect, one would want dielectric materials with large and nearly equal indices of refraction. However, there are other constraints associated with the choice of materials. For instance, for low index contrast one needs more layers to get close to the saturation limit. Calculation shows that for a refractive index difference of 0.1, one needs about 30 bilayers \((N=30)\) to make the difference in saturation times apparent, whereas for an index difference of 0.2, the number of bilayers needed is reduced to <20. Another constraint is related to the spectral width of the gap. Because I need high resolution for time delay measurements, the bandwidth of the single photons should be large, but all of this bandwidth must be contained inside the bandgap. Therefore, an index difference between 0.2 and 0.3 is fairly optimal for my conditions, Fig. 3.6.

To satisfy the constraints above, I choose samples with \(\approx 15\) bilayers \((N=15)\) of TiO\(_2\) and HfO\(_2\) with nominal indices of refraction of \(\approx 2.19\) and \(\approx 1.97\), respectively, when deposited as
Figure 3.6. 2-D plot of the propagation delay dependence on the refractive indices of the materials. For higher propagation delay difference one needs lower index contrast of the two dielectric film materials.
amorphous films. Both materials have a negligible absorption at the wavelength of interest (702 nm). The sample consists of four stack configurations deposited by coating: (HL)$^{15}$H, (LH)$^{15}$L, (LH)$^{15}$, and (HL)$^{16}$ on a fused silica substrate. There are 2 uncoated regions on the sample which are used as reference points for the measurements, Fig. 3.7. The other side of the substrate is antireflection coated. This was done to limit the high fringing effects of the substrate on photon delay times produced by the substrate-to-air interface.

Nominally, all four stack regions have a total thickness of 2.5 µm, with individual layer thicknesses $d_{Ti}$ and $d_{Hf}$ being 0.080 µm and 0.089 µm, respectively. It should take 0.585 fs for a photon to traverse those distances in either material as they both have the same optical path-length, i.e. $\lambda/4$. Note that a photon traveling the same distances (0.080 µm and 0.089 µm) in vacuum would traverse the regions in 0.27 fs or 0.30 fs, respectively. By measuring the difference between the transit time of a photon traveling through a single stack and a photon transiting a reference path, a 0.315 fs delay would be observed for a TiO$_2$ layer and a 0.285 fs delay through a HfO$_2$ layer. Interestingly, the measured delays through various stack structures do not correspond to a simple addition of the propagation delays through the individual layers. This is true even though (HL)$^N$H and (LH)$^N$L have the same optical (but not physical) thickness. All four stack structures appear nearly structurally identical, while their overall optical properties differ significantly.

3.6 Using HOM to measure propagation times

To measure propagation delays through dielectric stacks where the overall transit times, estimated simply using the thickness of the stack, are expected to be on the femtosecond scale, I choose to follow the methods of Ref. [19]. The first stage of this experiment is to create twin
Figure 3.7. A diagram of the sample surface. Four types of dielectric stacks are deposited on a single surface along with reference regions.
Figure 3.8. Experimental apparatus. Two photons are created via parametric down conversion and sent to a Hong Ou Mandel interferometer. The sample holder positions the reference and sample regions into and out of the beam. A piezo actuator (PZT) provides fine motion control (with resolution of 0.2 nm) of the pathlength for scanning over the Hong Ou Mandel dip. When the Start detector records photon arrival, it starts the clock that is stopped when the Stop detector clicks with the arrival of the second photon.
photons at 702 nm. I use type I non collinear PDC, see Ch. 2, with a birefringent LiIO3 crystal. A Coherent Innova 90 argon ion laser is used as a 351 nm pump beam. By adjusting polarization of the pump using a half wave plate, I generate single photons born two at a time with orthogonal polarizations. The crystal is mounted at the center of rotation with two fiber couplers at the edges of the arms. To couple identical photons, I find the correct phase-matching angles, which I calculate to be close to 5°, and adjust couplers appropriately. To align the pointing of the coupler, I connect fiber coupled lasers to them and back propagated the beams to the center of the crystal. With the Innova 90 running, I made sure that all the three beams intercepted there as well. Once the couplers are roughly aligned, they are connected to the single photon detectors and counts are observed while changing the position of the lever arms. Once the detectors record single photons, the count can be maximized by adjusting coupling angles and pointing while observing changes in count rates. When each detector observes a photon from a PDC pair, a coincidence count is recorded.

To establish interference between the photons, I have to ensure that they are identical when they arrive to the beamsplitter. Since they are born simultaneously, they have the same spectral and spatial features. Therefore, their polarizations must be the same. This is accomplished by placing polarizers and half wave plates at the exit of the output couplers. Polarizers are used to filter out any photons with polarization scrambled by propagating in fiber and half wave plate adjust the overall polarization to maximize the throughput.

Propagation paths of the two photons also have to be equal for them to be indistinguishable at the interferometer. A prism mounted on top of a translation stage is used for coarse adjustments of the path, giving 5 cm of movement freedom. A mirror mounted on top of
a piezoelectric (PZT) actuator is used for fine adjustments. After a rigorous search for an appropriate PZT I settled on a closed loop 500 micron system from Physik Intrumente, see Fig. 3.8.

A Hong-Ou-Mandel (HOM) interferometer is used to determine with high precision any relative changes in the propagation delay of two identical photons. One of the photons is sent through a dielectric structure, while the other travels through a path of known length. The two photons are then recombined at a beamsplitter. By overlapping the photons’ wavefunctions at a beamsplitter, I observe a drop in the coincidence counts between detectors in the two output ports of the beamsplitter. This is because quantum interference causes both photons of an exactly matched pair entering the beamsplitter to exit from the same port of the beamsplitter. If the spatial or spectral overlap of the wavefunctions does not exactly match, the interference will be incomplete. As the relative pathlength difference of the two arms is scanned, the reduction of coincidence counts occurs, giving rise to the HOM dip. Degenerate downconverted photons at 702 nm are selected in the present experiment by a 10 nm bandwidth interference filter at one detector and by a 15 nm bandwidth filter at the second detector. This asymmetry fundamentally limits the visibility of the HOM dip in my experiments [7].

3.7 Measurement

With no stack in place, my setup produces ≈ 200,000 photon counts per second for each channel and ≈3500 coincidences per second (background signal ≈ 400 counts per second). The HOM dip visibility is ≈ 80%. To test the interferometric stability of the setup, I position the sample stage to place one of the reference regions of the sample in the beam. I then scan
over the HOM dip 84 times during a 3 hour period. The fit of the dip minimum for each of the scans is calculated, obtaining a standard deviation of 0.33 fs, see Fig. 3.9. To measure tunneling times through each of the 4 stacks, the HOM dip position is found with the stack in place and compared it with one for a reference region. This measurement was performed ≈300 times over a 5 hour period, obtaining ≈300 datapoints for each stack structure (with the exception of (HL)\textsuperscript{15}H, for which ≈800 points were taken due to low transmission). To reduce the effect of various drifts, I average reference scans taken before and after each data scan. The background-subtracted HOM visibility is measured for all stacks and reference points.

### 3.8 Results

For each of the four stack types and reference regions I took over 300 HOM traces. The averaged and background-subtracted coincidence signal for the two odd-layer stack structures and reference regions can be seen in Fig. 3.7. By finding the average location of the HOM dip minima for the reference and sample regions, I calculate apparent pathlength differences and obtained corresponding propagation delays $\Delta \tau$. The measured $\Delta \tau$ is the delay relative to the propagation of light in vacuum through a distance $l$ equal to the stack thickness, $\Delta \tau = \tau - l/c$. The measured $\Delta \tau$ for all the structures are presented in Table 3.1 and Fig. 3.11. The experimental results are in excellent agreement with the theoretical model. Note that the theoretical calculation used no fitting parameters. Thus, I confirm experimentally that the traversal times can be very sensitive to subtle changes in a sample’s structure. In particular, the two unpaired-layer structures, with the same number of layers and exactly equal optical path lengths, produce propagation delays that differ by $10.99\pm0.58$ fs solely because of the different
Figure 3.9. Continuous scan of an HOM dip to test interferometric stability of the setup.
first and last layers. Note that this delay difference is larger than the propagation delay through the entire \((HL)^N H\) structure. Interestingly, the shorter time corresponds to an apparent superluminal propagation delay, while the longer time is \(\approx 2\) times longer than the luminal delay.

### 3.9 Conclusions

In conclusion, I present a measurement of propagation delays of photons that traverse a stop band of quarter-wave dielectric stacks that have both even and odd numbers of layers. I find experimentally that, as predicted in [21, 22, 23] dielectric stack samples of the same approximate thickness and with similar structure can yield very different traversal times. That is, small structural changes in the dielectric stacks play a large role in the determination of propagation times of photons (Hartman saturation level). Indeed the addition of a single layer can alter these times up or down by many times what would be expected from the transit time across the layer in isolation.

<table>
<thead>
<tr>
<th>Sample</th>
<th>Predicted delay, fs</th>
<th>Experimental delay, fs</th>
<th>Reference visibility, %</th>
<th>Sample visibility, %</th>
</tr>
</thead>
<tbody>
<tr>
<td>((LH)^15 L)</td>
<td>7.70</td>
<td>7.60 ± 0.35</td>
<td>78.60 ± 0.13</td>
<td>78.20 ± 0.19</td>
</tr>
<tr>
<td>((LH)^15)</td>
<td>3.59</td>
<td>4.38 ± 0.40</td>
<td>79.06 ± 0.14</td>
<td>78.82 ± 0.36</td>
</tr>
<tr>
<td>((HL)^16)</td>
<td>0.68</td>
<td>-0.49 ± 0.43</td>
<td>72.56 ± 0.19</td>
<td>72.22 ± 0.42</td>
</tr>
<tr>
<td>((HL)^15 H)</td>
<td>-3.89</td>
<td>-3.39 ± 0.46</td>
<td>80.45 ± 0.23</td>
<td>79.43 ± 0.82</td>
</tr>
</tbody>
</table>

Table 3.1. Predicted and measured delays and dip visibilities.
Figure 3.10. HOM dip profiles. The reference is an uncoated substrate (open circles and dotted lines). Sample regions are a) (LH)$^{15}$L and b) (HL)$^{15}$H (closed circles and solid lines). The sample profiles are scaled as indicated on the figures. The uncertainties associated with the datapoints are smaller than the size of the symbols.
Figure 3.11. Theoretical prediction of propagation delay times for different dielectric stack configurations. Each of the structure types produces a different propagation delay branch of the graph. The line represents propagation delay of a photon in an equivalent thickness of vacuum. Values below the luminal line represent superluminal propagation. Values above the luminal line represent subluminal propagation. Large symbols show experimental measurements with uncertainties being about half the size of the symbols.
CHAPTER IV

HOM DIP VISIBILITIES: A NEW DIMENSION IN HOM SENSING.

4.1 Introduction

The phenomenon of nonzero probability of finding a particle propagating through a potential barrier is a unique consequence of quantum mechanics that has been widely researched in modern science. Although barrier propagation is currently well understood by scientists, some questions still remain unanswered, such as apparent superluminality of propagation of photons. Such a phenomenon seems to violate the principle of causality. Steinberg et al. first observed superluminal propagation delays (-1 fs) through dielectric bandgap structures using single photons for measurement [19]. This result is confirmed by my efforts [29]. However, I also find that seemingly negligible changes in the structure of the dielectric stacks produce high variations of the propagation delays, ranging from sub- (8 fs) to superluminal (-4.8 fs). Although this proves the dielectric stack model to be inappropriate for optical tunneling, it is necessary to understand whether this result violates causality in a quasi-stationary limit. Since all of the equations describing dielectric stack model and tunneling models, such as frustrated total internal reflection and waveguide used below cut off wavelength, are described using Maxwell equations, causality is not violated.

While the work of Ref. [19] tested for wavepacket distortion and pulse reshaping, the limits put on such reshaping were not strong, and it is pointed out in [23] that only very subtle distortions in the transmitted wavepacket or wavefunction are required to obtain the appearance of superluminal effects. If the incident pulse is a Gaussian wavepacket and the “reshaped” (delayed or advanced) pulse is Gaussian as well, then they will be impossible to distinguish in an
interferometer. The evidence of distortion in the transmitted pulse or wavefunction may be hard to detect; if it looks enough like the reference pulse, an interferometer cannot, for instance, tell one Gaussian from another.

Transit time measurements through a series of dielectric stacks have been performed by Spielmann et al. [25] using 3-8 femtosecond laser pulses. These authors report that the transit time becomes monotonically independent of the barrier thickness as the barrier becomes more opaque. The measurements are made, however, on similar dielectric stacks - ones that varied only by adding more high- and low-index layers in pairs. As has been pointed out since then, the transit time is not expected to saturate monotonically if, instead, layers are added to the stack one at a time [21, 22, 23].

In the case of Ref. [25], the optical bandgaps were made much more opaque than in [19] and the event rate was kept up by having many photons in each pulse. In this case the pulse bandwidth was also large enough to observe some obvious pulse distortion. Pulse narrowing resulted, from a spectral point of view, from the transmission variation of the bandgap over the spectrum of the pulse; suppressing the center frequencies and effectively broadening the spectrum of the transmitted pulse.

The apparent superluminal behavior can be explained as a consequence of spectral envelope reshaping, where the outcoming spectral wavepacket has changed its shape so the maximum of the peak is shifted forward and, therefore, is the cause for the apparent superluminality. I believe that, as a result, this distortion may be large enough to be measurable in an experiment. In this chapter I investigate the effects of a bi-photon wavepacket modulation on experimental outcome of time delay measurement. I am interested in investigating how this
modulation affects the interferometric picture observed in the experiment and whether by analyzing it one can put a boundary on photon reshaping that took place as a result of the measurement.

4.2 Methods

In the above mentioned experiments [19, 23, 29], single photon pairs are created using the process of parametric down conversion (PDC) and were then sent through two arms of the Hong Ou Mandel (HOM) interferometer. One of the photons has to traverse a dielectric bandgap structure and then interferes on a beamsplitter with its twin. By observing the shape of the resulting interference pattern, specifically the location of the HOM dip, the researchers are able to determine the delay between propagation through the bandgap structures vs. propagation through the same thickness of air. Although it is the HOM dip location that is of interest because it conveys the information about the time delay, I was also curious to take note of the HOM visibility change. Steinberg et al. note that the visibility remained the same for the case where both photons are traveling through air and for the case where one of them is traversing a potential barrier. However, in this experiment I notice that visibilities differed slightly. I believe that by studying these differences in the visibility of the interferometric picture, I will be able to assess the amount of distortion that takes place due to barrier traversal.

4.3 Theoretical modeling

Here I begin with modeling of the PDC process that creates a pair of identical photons born simultaneously. The state of the PDC generated twin photons is given by
\[ |\Psi(t)\rangle = M|\text{vac}\rangle|\text{vac}\rangle + \]
\[
\frac{\eta V \delta \omega}{2\pi} \sum_{\omega'} \sum_{\omega''} \varphi(\omega', \omega'') \frac{\sin \frac{\omega' + \omega'' - \omega_b}{2} t}{\omega' + \omega'' - \omega_b} \exp(i(\omega' + \omega'' - \omega_b) \frac{\omega}{2}) |\omega'\rangle_i |\omega''\rangle_i + \ldots, \tag{4.1}
\]

where \( \varphi(\omega_1, \omega_2) \) is the spectral distribution function of the two-photon wavepacket, and \( \omega_1, \omega_2 \) are respective photon frequencies [7]. In the case of unmodulated twin photons, \( \varphi(\omega_1, \omega_2) \) is symmetric and has a maximum at \( \omega_0/2 \).

Since in single photon traversal experiments only one of the photons is forced to interact with a potential barrier while the other is used for reference, I only alter the spectral function of one of the bi-photons. Assuming Gaussian nature of the bi-photon spectral function, I introduce a modulation to one photon’s spectral distribution function (Fig. 4.2) by setting
\[
\varphi(\omega_1, \omega_2) = \exp\left(-\frac{(\omega_1 - \omega_b)^2}{2\sigma^2}\right) \exp\left(-\frac{(\omega_2 - \omega_b)^2}{2\sigma^2}\right)(1 - A \cos(j(\omega_2 - \omega_b/2))), \tag{4.2}
\]

where \( A \) and \( j \) are amplitude and frequency of the modulation, respectively. This function can be rewritten in the following form:
\[
\varphi\left(\frac{\omega_0}{2} + \omega, \frac{\omega_0}{2} - \omega\right) = \exp\left(-\frac{\omega^2}{\sigma}\right)(1 - A \sin(j \omega)). \tag{4.3}
\]

This describes a spectral envelope modulation at an arbitrary modulation frequency \( j \). Because the optical materials of the barrier are linear, any spectral distortion can be described as a superposition of sinusoidal modulations (8). See Fig. 4.1. By adjusting the value of the modulation amplitude \( A \) and frequency \( j \) I control the amount of distortion in the wavepacket, where \( A = 0 \) is the original unaltered photon and \( A = 1 \) provides the maximum physically significant amount of modulation.
Figure 4.1. Effect of sine modulation on a Gaussian wavepacket. Increasing amplitude $A$ causes more modulation to appear on the surface of the wavepacket.
To understand the effects a modulation (4.2) has on the overall shape of the HOM dip produced as the twin photons recombine on an HOM beamsplitter.

In the simple model of the HOM interferometer, the twin photons pass through a beamsplitter and get collected by the detectors, Fig. 4.2.

Electric fields at the exit ports of the beamsplitter can be described as:

\[
\hat{E}_3^{(\text{c})}(t) = \left( \frac{\delta \omega}{2\pi} \right)^{\frac{1}{2}} \sum_\omega T \hat{a}_s(\omega) \exp(-i\omega(t - \tau_1)) + R \hat{a}_i(\omega) \exp(-i\omega(t - \tau_2)) ,
\]

\[
\hat{E}_4^{(\text{c})}(t) = \left( \frac{\delta \omega}{2\pi} \right)^{\frac{1}{2}} \sum_\omega R \hat{a}_s(\omega) \exp(-i\omega(t - \tau_1)) + T \hat{a}_i(\omega) \exp(-i\omega(t - \tau_2))
\]

where \( R, T \) are complex amplitude reflectivity and transmissivity, \( \hat{a}_s, \hat{a}_i \) are creation operators,

Figure 4.2. Schematic of the Hong-Ou-Mandel interferometer. The twin signal and idler photons are recombined at the beamsplitter and detected by the detectors.
and $\tau_1$, $\tau_2$ designate the time of the photoelectronic detections. The joint probability density that a photon is detected at port 3 at time $t$ and another one at port 4 at time $t + \tau$ is then expresses as

$$P_{3,4}(t, t + \tau) = \alpha_3 \alpha_4 \left\{ \Psi(t) \left[ \hat{E}_{3}^{(-)}(t) \hat{E}_{4}^{(-)}(t + \tau) \hat{E}_{3}^{(+)}(t + \tau) \hat{E}_{4}^{(+)}(t) \right] \right\} \Psi(t) \right\}$$

(4.6)

where $\alpha_3$, $\alpha_4$ are detectors’ efficiencies. By substituting equations (4.4), (4.5), and (4.1) into (4.6), one can simplify it to

$$P_{3,4} \propto |T|^4 |G(\Delta \tau + \tau)|^2 + |R|^4 |G(\Delta \tau - \tau)|^2 - R^{2*} T^{2*} G^*(\Delta \tau + \tau) G(\Delta \tau - \tau) - R^{2*} T^{2*} G^*(\Delta \tau - \tau) G(\Delta \tau + \tau)$$

(4.7)

with $G(\tau) = \int_{-\infty}^{\infty} \phi \left( \frac{\omega_0}{2} + \omega, \frac{\omega_0}{2} - \omega \right) \exp(-i\omega \tau) d\omega$.

(4.8)

To calculate the coincidence rate $R_{3,4}$, one can take an integral of the probability function

$$R_{3,4} = \int_{\tau_3}^{\tau_4} P_{3,4}(t, t + \tau) d\tau$$

where $T_R$ is the resolving time of the detector. Because the resolution of single photon detectors is on the order of nanoseconds, while the measured effect deals with delays of just a few femtoseconds one can safely assume $T_R$ to be infinity.

By taking the integral of (4.7) to calculate the coincidence rate, one can obtain

$$R_{3,4} \propto (|T|^4 + |R|^4)(1 + \frac{A^2}{2}(1 - \exp(-\frac{1}{2} j^2 \sigma^2))) -$$

$$\left( R^{2*} T^{2*} + R^{2*} T^{2*} \right) \exp\left(-\frac{\sigma^2 \Delta \tau^2}{2} \right)(1 + \frac{A^2}{2}(\exp(-\frac{1}{2} j^2 \sigma^2) \cosh(j \Delta \sigma^2) - 1))$$

(4.9)

Of interest here is the effect of the frequency of the oscillation on the visibility of the HOM dip profile. In the case when $j \to 0$, or low modulation of the wavepacket,

$$R_{3,4} \to (|T|^4 + |R|^4) - \left( R^{2*} T^{2*} + R^{2*} T^{2*} \right) \exp\left(-\frac{\sigma^2 \Delta \tau^2}{2} \right) \text{ and has no dependence on the amplitude of}$$

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modulation. On the other hand, for the case $j >> 1/\sigma$, high frequency modulation,

$$R_{3,4} \to (|T|^4 + |R|^4)(1 + \frac{A^2}{2}) - (R^2T^2 + T^2R^2)\exp(-\frac{\sigma^2 \Delta \tau^2}{2})\exp(-\frac{A^2}{2})$$

and is independent of $j$.

Upon further examination of this result, one can find it to be a monotone. Of particular interest to us is the change in visibility of the HOM dip. Here one can see that by increasing the amplitude of the modulation of the photon wavepacket, one observes a decrease in visibility of the dip. Uncertainty in the dip visibility can also be used to describe the noise in the spectral density function due to a barrier.

4.4 Results

An important question is the extent to which wavepacket distortion affects the measured transit times and results in apparent superluminality. Such distortion would present itself as a change in the measured visibility of the HOM dip [27]. I use a simple model that ties such a visibility change to the wavepacket distortion by introducing a sine modulation, described above. Here, $\phi_0$ is the unmodulated two-photon spectral function [7], $A$ and $j$ are the amplitude and frequency of the modulation, respectively. $V$ decreases monotonically with the modulation amplitude $A$, and does not depend on $j$. Thus, by observing changes in dip visibility, one can assess the overall effects of distortion caused by the barrier traversal on the wavepacket under this model. It is, therefore, interesting to determine the degree of this change in the experiment described in Chapter 3.

To detect any possible distortions of a wavepacket that undergoes tunneling, I measured a background-corrected visibility of the dip, presented in Table 3.1 and Fig. 4.4. I see that the
Figure 4.4  
Relative HOM dip visibilities for the four stack types.
difference in the visibilities observed is on the order of the uncertainties. This result allows us to bound the wavepacket distortion, explicitly, $A < 0.185$ (or 18.5%), with a 95% probability under the model discussed above. This limit on wavepacket distortion indicates that a quasi stationary approximation [28] may be still valid under these conditions.

4.5 Conclusions

This chapter describes another dimension of HOM measurements that utilizes the change in the visibility of the HOM profile. The observed visibility difference of an HOM dip can be used to describe a change in a spectral function of a signal compared to idler. The amount of change is linked directly to the amount of distortion in the spectral wavepacket. Using this method, I am able to further analyze the results of the HOM measurement described in Ch. 3 and put a limit on the maximum amount of distortion taking place as a result of barrier penetration.
CHAPTER V
INTERFERENCE OF FLYING AND STATIONARY QUBITS.

5.1 Introduction

In the previous chapters I show that a Hong-Ou-Mandel (HOM) interferometer is a quantum sensor able to determine if different propagation paths could make photons that were born indistinguishable different. Similarly, it can be used to determine if the two photons that come from different sources are indistinguishable photons. Indistinguishability of the quantum states such as these carried by single photons is key in making quantum interfaces, devices that map entanglement from one material system to the other. The key practical reason to move entanglement across platforms is that various material systems have different, sometimes incompatible, properties. One way to propagate an entanglement between material systems is described in [32]. Establishing such entanglement between single photons produced via different mechanisms could link various material subsystems into a single quantum network. For example, it could aid in interconversion between quantum memory (media with low coupling to cap decoherence) and quantum gates (media with high coupling to promote qubit interaction), complementing research in manipulation and scalability of qubits.

The experiment is largely concerned with tailoring the properties of photons generated in the SPDC process and trying to match them closely to those of the quantum dot (QD) excitons. This is an essential step in establishing indistinguishability between flying and stationary qubits. One can gauge the degree of success by the visibility of the dip produced as a result of HOM interference between the qubits, as described in Ch. 2.
Many schemes for scalable optical components for quantum computing rely heavily on interfering qubits produced by various single photon sources. Thus, scalability of the components and sources is of major importance. Both QD excitons and PDC photons are excellent candidates for quantum bit processing described above. QDs have large dipole moments and there are tunable parameters that can be changed to design excitons of desired properties. They take advantage of the well established semiconductor processing technology, which makes integration as well as scalability possible. On the other hand, SPDC is a well established technique for producing correlated photons used for quantum communication demonstrations extensively. One of the advantages of SPDC is that it can be engineered to produce photons of practically any desired wavelengths and wavepackets.

Single photon interference is known to take place when two photons are indistinguishable at a beamsplitter. To satisfy the requirement, the photons can be generated by the same process or be tailored to match each other. It has also been shown by Mandel [33] that quantum interference occurs when the two input photons are indistinguishable, i.e. any measurement cannot tell the two apart, even in principle. He predicted a possibility to interfere the photons from the two sources of different nature, provided that their carrier frequencies are the same and coherence times of the two sources is larger than detector resolution. In a recent work by Bennett et al. [34], the authors show the experimental implementation of this phenomenon. They used a continuous wave (CW) laser combined with single photon signal from a QD source to observe second-order interference. The two sources are not synchronized nor have similar coherence times. By changing polarization of one of the sources, one can force the photons to be distinguishable. In this way the base line is taken. Note the partially covered dip of second-order
cross correlation function $g(2)$. When the two sources of photons are mixed on a beamsplitter, the probability of detecting a pair at zero delay dramatically increases. However, because one of the sources is antibunched (i.e. has a significant dip in its $g(2)$) the resulting mixture of the two fields remains antibunched, to a lesser degree. Here it is important to stress that no interference takes place in this measurement.

For parallel polarizations, interference is turned on. The interference results in observing a dip of larger depth. The mechanism of interference is similar to that described previously, i.e. due to coalescence of the two fields in a state containing an abnormally larger fraction of photon pairs. Thus, they observed partial indistinguishability of the two different fields with the same polarization. Note that this effect can only be observed with fast detectors (time response should be better than either of the two sources’ coherence times). As a result, since the detectors are not infinitely fast, the dip observed is shallower than theoretically possible. This effect of indistinguishability on a short time scale occurs because the differences in wavefunctions cannot be detected, even in principle, during those observation times. This effect therefore can only be seen in post-selection, i.e. after the detections took place. Due to post-selection this method is not scalable. Also, attenuated lasers cannot generate single photons that can be used for entanglement, however the reasons for this are beyond the scope of this work.

It is necessary for the two qubits to be truly indistinguishable, i.e. without restricting measurement times, to maximize quantum interference and generate potentially scalable entanglement. Since different sources produce fields with distinctly different spectral, temporal and spatial signatures, it is extremely challenging to achieve a significant interference
between photons that are not created by sources of similar nature. As a result, quantum interference with dissimilar quantum fields has not yet been realized. Distinct quantum dot sources are also not identical, showing a large distribution in emission wavelengths and bandwidths. One attempt, however, has been made to entangle excitons from two quantum dot systems by Sanaka et al. [35]. He observes a dip in coincidence counts when the photons arrive to the interferometer at the same time. Although this dip indicates interference between the two incoming photons, its visibility is around 40%, indicating the absence of quantum interference. I attempt to reproduce this result with APD detectors. Since the integration time of the APD detectors is still relatively short, I observe interference of the single photon field with a coherent state field. The results of these efforts are presented in Fig. 5.1. This experiment is used as preliminary test, prior to attempting interfering two single photon fields from PDC and QD sources. One can gauge the degree of the success by the visibility of the dip produced as a result of HOM interference between the qubits, as described in Ch. 2.

This research has a potential to become a major step toward the goal of directly recording a single photon field, created during SPDC process into an exciton created by exciting a QD. A QD, in turn, can be used as a quantum gate to perform operations on flying qubits that are delivered to it. Interconnecting such different physical systems provides a new path towards coherent control. This experiment is largely concerned with tailoring the properties of photons generated in the SPDC process and trying to match them to those of the QD excitons as closely as possible. This is an essential step in establishing indistinguishability between flying and stationary qubits.
Fig. 5.1. Correlation function of the laser-qd interference experiment. A larger dip is seen for the case of parallel interference, indicating coalescence.
5.2 Experimental Set Up

To synchronize the timing of the photon pulses generated by both the QD and SPDC single photon sources, I use a single pump laser TiSaph Mira for simultaneous excitation. The laser output is pulsed, with pulse duration around 6 ps, and an emission wavelength centered at 820nm. The InAs/GaAs QD sample can be excited with 820 nm pulses reasonably well. The exciton emission wavelength is close to 920 nm, slightly different for each dot. To match such QD source, a system is designed to convert 820 nm laser pulses into pairs of single photons, where one photon has a matching carrier frequency (~920nm). Before down converting the light pulses using SPDC, I start by up converting the 820 nm pulses using second harmonic generation (SHG). SHG is a second order nonlinear process, similar to SPDC (see Ch. 2). Here I use a BBO crystal to generate pulses at 410 nm. Two Watts of 820 nm laser pulses are able to produce 70 mW of 410 nm blue laser pulses. To filter out any aberrations caused by the crystal structure the beam is coupled into a single mode UV fiber and sent through the oven with the SPDC crystal.

Since I am interested in getting the highest possible correlated photon pair count rate, while using 410 nm wavelength, I use periodically poled KTP (ppKTP) crystal from Raicol for the SPDC. The poling period is calculated for quasi-phasematching and desired operating temperature of 50°C for 918 nm photon production taken into account. The temperature is often used as the last, fine-tuning “knob” that phase-matches the crystal for the desired SPDC process. The design temperature is chosen to be higher than room temperature ensure that the crystal would not have to be cooled, since that poses many experimental problems, such as water vapor condensation. To maintain a constant and uniform temperature of the crystal it is placed into a
Thorlabs PV40 oven. In this experiment, the crystal used 410 nm photons of extraordinary polarization as pump photons and collinearly emitted 918 nm ordinary and 741 nm extraordinary polarized photons (type II SPDC). Since the process is collinear, a polarized beam splitter (PBS) is used to split the two photons and process them individually.

One of the main challenges in this experiment was to be able to match the spectral and spatial shapes of the QD and SPDC photon wavepackets exactly. Temperature tuning of the ppKTP crystal allowed for some variation in the carrier wavelengths of the produced pairs of photons. It is also important to match the spectral bandwidths of the QD excitons and SPDC photons. I am using a holographic volume Bragg grating (VBG) to pre-filter 918 nm photons to 0.2 nm bandwidth followed by a Fabry-Perot (FP) cavity that is tunable to select the exact bandwidth that is desired for the experiment.

VBG’s are very similar to the gratings described in Ch. 3. They are quarter wave layer stacks that take advantage of destructive interference to create a nearly perfect mirror. In a volume Bragg grating, however, the stacks are holographically imprinted into bulk glass at an angle designed for a specific wavelength selection (i.e. Bragg conditions). These gratings have a range of ± 2 nm around the design wavelength, which will further allow us to modify the setup for different QD excitons. At the wavelength of 918 nm VBG provided a reflection at ≈5° angle from the normal with 99.5% efficiency.

The FP cavity consists of two slightly concave mirrors that are aligned parallel to each other. The mirrors have reflectivity of 95% and the concavity compensates for any slight misalignment. The distance between the two mirrors is adjustable and determines the wavelength of the exiting primary mode of the beam. Placement of the cavity is essential to
maximizing transmittance. The waist and location of the focused beam exiting the cavity was calculated using a knife edge measurement, where a sharp razor blade mounted onto a translation stage is used to block the beam and determine its characteristics. Similarly, the incoming beam was characterized and adjusted to match the cavity properties exactly. Once the FP cavity is aligned, it has an efficiency of 87%. The correct longitudinal mode of exiting light can be found by applying varying voltage on the piezoelectric (PZT) stacks that are placed between the two mirrors. One of the problems I face with the PZT stacks is that they have a tendency to drift when constant voltage is applied. Since the drift is slow (on the order of 100kHz/second) I can use a LabView program that updates voltage on the PZT at 10-20Hz to lock the cavity and compensate for the drift. A second frequency stabilized laser beam at 830 nm is coupled to the same cavity, and in the same transverse mode as the main HOM beam. I take advantage of the VBG Bragg reflector properties, because it fully transmits light if it is not in Bragg resonance (less residual reflection from anti-reflection coating). In this way I separate the locking beam from the main signal at 918 nm with no extra components introduced into the 918 nm path. The transmitted light is then collected, filtered from any residual part of the HOM beam and coupled into a fast detector that is connected to a computer. A LabView program is then used to find a location of the primary mode and lock the position of the PZT to a specific value of the curve.

Once the single photons are prepared to match the QD photons, I send them to a HOM interferometer to determine the degree of their mutual indistinguishability. Based on the parameters of the QD photons previously observed, I calculate the width of the dip to be close to 1 m. Therefore, to vary the two wavepackets distinguishability I adjust polarization of the SPDC photons from parallel to that of the QD (maximal indistinguishability) to perpendicular (full
distinguishability), as opposed to separating wavepackets longitudinally in space, as it is traditionally done.

I use 741 nm photons from SPDC process to herald 918 nm photons. Here I am only interested in detecting the heralding photon and it has no requirement of being indistinguishable with the QD exciton. Therefore, I do not need to perform extensive operations to “shape” 741 nm photons. Nonetheless, in addition to filtering idler (heralding) photons from the remaining pump and occasional signal photons, I send it at a VBG Bragg grating with sharp (0.1nm) reflecting resonance to filter idler photons whose conjugates will definitely be rejected in an HOM path (not matching the QD). Such a rejection is possible due to energy conservation in SPDC process.

The simplified setup is presented in Fig. 5.2. Two single-photon avalanche detectors (SPADs) monitor the outputs of the HOM beamsplitter. Another SPAD is used for detection of heralding photons. The electrical output of the SPADs is collected using a timestamping board. The timestamps are processed to extract statistical dependences.

5.3. Experimental Results

After rigorous spectral filtering of PDC and QD photons, I analyze their spectral and temporal characteristics and used a Lorentzian fit to model them. The resulting PDC photons have transmission peaks with full width at half maximum (FWHM) of $\Delta \nu_{\text{PDC}} = 0.9 \pm 0.1$ GHz and temporal pulse duration of 0.14 ns. Using a Fabry-Perot cavity, similar to the one described above, I found QD emission linewidth of $\Delta \nu_{\text{QD}} = 0.9 \pm 0.1$ GHz, with a coherence time of
The coherence time, $T_2 = 0.29$ ns and lifetime of $T_1 = 0.83$ ns. Thus, the two sources a very closely matched, see Fig. 5.3.

To check the single photon nature of the QD source, a Hanbury Brown—Twiss correlation measurement was performed [39]. The QD photon signal was sent through a beamsplitter and collected by the single photon avalanche detectors (SPAD) and the second order correlation is computed. The results of this measurement can be seen in Fig. 5.4. The amplitude of the peak at time 0, 16.5% of the average neighboring peaks, indicates single photon nature of the source.

There are issues that are important to mention in regard to the QD source in this experiment. Since the QD coherence time is so much smaller than its lifetime and is not limited by it, it is important to mention the effects of decoherence on this system. Quantum decoherence, or dephasing, occurs when a quantum system interferes with the environment in a thermodynamically irreversible way, giving the appearance of a wave function collapse. This, in turn, prevents quantum interference of such system, causing limitations on coalescence in my experiment. I also observe that the QD line is split, i.e., it consists of two peaks of orthogonal polarization. Further filtering was applied to single out one of the peaks for my experiment.

Once the two sources are combined at the beamsplitter, I determine the degree of interference of the two sources by measuring the second order cross-correlation of the output ports of the beamsplitter. I herald the PDC photon arrival, i.e., I only take into account the events that take place when the idler photon (heralding photon) is detected, indicating the presence of the signal photon at the beamsplitter. The correlation function for the cases of QD and PDC photon polarizations being parallel and orthogonal are measured and the difference in
Figure 5.2. Experimental apparatus. A pulsed laser excites QD and PDC. A photoelectronic detection on SPAD_HRLD heralds a presence of a single photon in one arm of the interferometer, while a quantum dot supplies single photons to the other arm. The number of coincidences is observed on the two SPAD_HOM detectors. If the photons produced by QD and PDC indistinguishable, at least partially, the number of coincidences will be suppressed. A ½ wave plate is used to adjust the polarization of input PDC photons to be either parallel or perpendicular to that of QD photons.
Figure 5.3. I characterize my sources: Linewidth of PDC (a) and QD (c); temporal properties of PDC (b) and QD (d).
Figure 5.4. Measured second-order autocorrelation of a QD. The periodically emitted photons from the pulsed excitation lead to peaks at multiples of the pulse repetition time (13 ns). The reduction of the peak at zero delay demonstrates single-photon character of QD emission.
the resulting peaks at time 0 are compared. The peaks in question are smaller than the neighboring peaks, since I am dealing with single photon sources. When the polarizations of the interfering photons are orthogonal, no interference takes place. Once the polarizations are matched, a change in the peak at time 0 indicates the degree of coalescence.

As shown in Fig. 5.5, the peak at time 0 of parallel polarization is lower than the one for perpendicular polarization. It is interesting to note, as seen in Fig. 5.5 b, that the difference in amplitude of the two peaks is much more pronounced at the maximum and much less so at the tails of the peak. This highlights the effect of decoherence on the system. Since QD photon lifetime is so much longer than its coherence time, the photon loses its ability to interfere at time delays longer than its coherence time. On the short time scale, however, the interference should be nearly perfect. However, the SPAD detector resolution is also on the order of the QD coherence time and I am not able to observe finer features of the peak in question. I am able to calculate a theoretical fit for the peak as seen in Fig. 5.5 b and to experimentally observe a 16 ± 3 % and calculate a theoretically possible 32 ± 3 % coalescence for the two sources.

Thus, I am able to interfere two photons from two different sources that have no common history and are of drastically different nature. I have shown that the quantum interconnect technique presented here, is indeed possible to realize for the photons generated by QD and PDC processes. To achieve a higher degree of coalescence, I need to improve the coherence time for the QD photons.
Figure 5.5 Measured conditional second-order crosscorrelation function (with a heralded PDC source). (a) For perpendicular polarization (red dots) the photons from the two photon sources are distinguishable. This gives rise to a peak at zero delay (within the same heralded trial). (b) The peak at zero delay, magnified, showing that the coincidence suppression is stronger for nearly simultaneous detections (in the center of the zero coincidence peak) because of decoherence effects of a QD. I also present the results of modeling, using the measured properties of QD and PDC. The only fitting parameter is the overall scaling coefficient. Red curve: perpendicular polarization (no interference); green curve: parallel polarization in the limit of instantaneous detectors; blue curve: parallel polarization with the time response of detectors used.
5.4 Summary

Establishing interference and entanglement between two distinctly different sources can prove to be very important for future quantum computing devices. Regardless of the interference outcome, this novel research will provide a deeper understanding of quantum photonic systems. In my measurement I am able to establish a 16% interference between QD and PDC sources. Future work involves reducing decoherence effects in the QD system by fabricating micropillar cavities around the QDs.
CHAPTER VI

FABRICATING MICROPOST CAVITIES.

6.1 Motivation

The success of the two photon coalescence in my experiment is limited by the decoherence of the quantum dot source. Therefore, in order to achieve higher degree of PDC – QD photon interference, one needs to improve the quality of the QD source. To achieve this, one can pattern pillars, which act as microcavities around the QDs and exhibit three-dimensional photon confinement. They are fabricated using chemically assisted ion beam etching. Examples of such cavities can be seen in [37]. The pillars are deposited in a random process, enclosing several quantum dot structures within it. Once the nanofabrication process is completed, one needs to carefully inspect the sample, locating the pillars with one or two quantum dots in resonance with the fundamental cavity.

Provided the success of pillar nanofabrication, I expect the resulting coalescence of QD and PDC sources to be close to 80%. The experimental procedures necessary to complete the experiment are exactly those described in Chapter 4 and will be completed outside of this work.

The next part of this research includes using quantum dot (stationary qubit) excitons and photons (flying qubit) created in the process of spontaneous parametric down conversion (SPDC) to generate indistinguishable photon states.

6.2 Photolithography Process

All micro and nanofabrication processes involve transferring a pattern onto the surface of a substrate from a mask. A process where a pattern is imprinted taking advantage of a
photosensitive thin film material is called photolithography. This requires ultraclean conditions, since 10% contamination of each mask step will result in a yield of less than 50% in a seven step lithography process. The facility used in this project is Class 100, averaging 100 particles larger than 0.5 microns and 0.65 particles larger than 5 microns per cubic foot [42].

One of the major problems for lithographic processes is lack of adhesion of resist to the wafer. The surface of the substrate needs to be clean and dry to avoid peeling. To ensure process reliability, a GaAs wafer is dehydrated for 10 minutes at 200°C on a contact hot plate prior to any resist application. To further improve adhesion the wafers undergo a soft bake (114°C) after each resist spin [42, 43].

After cleaning and baking, the GaAs wafer undergoes a bi-layer process where two thin film resists are used to create a barrier for pattern imprinting. First the wafer is coated with a layer of Microchem LOR3A chemical resist that serves as an undercut barrier. LOR resists are based on polydimethylglutarimide. While most resists require a layer of primer to ensure adhesion to a substrate, LOR is deposited directly onto a GaAs surface in a bi-layer process [43]. Once LOR is dry, a second layer of photosensitive material called photoresist is deposited. For this experiment I use Microposit S1813 positive resist, which is based on propylene glycol monomethyl ether acetate. Like LOR, S1813 is deposited in liquid form and spun on a vacuum chuck at speeds ranging from 3000 to 6000 rpm [44]. The spin speed determines the final thickness of the barrier deposited onto GaAs. It is an important variable in micro fabrication, as it limits the thickness of metal that can later be deposited on the GaAs surface.

During spinning the layer of resist tends to accumulate around the edges of the substrate. It is even more pronounced if the substrate is rectangular, having sharp corners. As a result, the
layer of resist around the edges can become 3 times thicker than that in the center of the chip. This can cause blurry features during the exposure process and needs to be removed prior to alignment. During the edge bead removal process the edges of the chip covered by positive resist get exposed by a high intensity UV light causing them to dissolve in a developer bath. The area of the chip that is not exposed is not affected by this process and can be later imprinted.

Once the edge bead removal is completed and the sample is covered by relatively even layer of resist, it is ready for mask alignment and exposure. A mask used for this experiment is a quartz plate with Cr deposited onto its surface to outline the features to be imprinted. To make micropost cavities, I use arrays of circles of different sizes, ranging from 1 micron to 20 microns. The coated sample and a mask plate are separated by 100 microns for alignment purposes and their respective positions are adjusted using an optical microscope. They are then brought into contact to eliminate dispersion of the UV source around the features on the mask, which can cause blurry features in the resist. All the areas that are exposed to UV light get washed away in the developer bath and the pattern that remains mimics the features on the mask.

6.3 Descuming Process

Once the resist on the surface of the chip is imprinted with a pattern, one has to ensure that no residual resist is left in the windows created by the lithographic process. Most commonly a Reactive Ion Etching (RIE) system is used to burn off the remaining resist in a process called descuming. The operating principles of an RIE tool are described in detail in section 6.6 below. Oxygen plasma is used to etch away part of the resist layer preparing the substrate for metal deposition. RIE provides both isotropic and anisotropic etches simultaneously, so while is it
primarily used to clean off the surface of the substrate, it also increases the undercut in the chemical resist.

6.4 Electron-Beam Evaporation

The electron-beam (E-beam) evaporation system consists of a vacuum chamber containing an electron beam gun. A beam of electrons with up to 15 keV of energy is focused on a target source to be evaporated. When the energy of the E-beam is increased sufficiently, it melts the metal target and forces it to be evaporated onto a substrate placed in the chamber. The wafers are placed into a dome that is suspended at the top of the chamber and is allowed to rotate to ensure even deposition. It is also often heated to ensure better adhesion of the film to the substrate. The evaporation targets themselves are placed in the crucibles at the bottom of the chamber and are water cooled. The surface of the targets only comes into contact with the E-beam to reduce contamination of the material. The size of the crucibles and the targeting material are relatively large to ensure sufficient amount of material being present for the deposition. [42, 45]

For a small planar source, the growth rate is given by

\[
G = \frac{m}{\pi \rho r^2} \cos \varphi \cos \theta
\]

(4.1),

where \( G \) is measured in cm/sec, \( \varphi \) is the angle measured from the normal of the plane of the source, \( \theta \) is the angle of the sample wafer to the evaporation stream, \( \rho \) is the density of the evaporating material, and \( m \) is its mass evaporation rate [42]. The growth rate is easily controlled during the evaporation process by adjusting the current and energy of the electron beam. It is then monitored during deposition by a quartz crystal. The crystal is allowed to be coated by the evaporated material during deposition. The shifts in its mechanical resonant
frequency is proportional to the amount of material deposited and by monitoring it the evaporation rate of the deposition can be calculated with 0.1 Å/sec precision. [45]

Although these systems are fairly user friendly, they have some disadvantages. If several metals are routinely evaporated in the same tool, some residual film is deposited onto the surface of the chamber and contaminates the targets, forming an alloy the next time the chamber is used. The total film thickness of the deposited material is limited by the amount of metal that is able to be placed in the target holder. In addition, if a composite material is needed for evaporation, these systems become very difficult to control. One of the two (or more) materials will have a lower melting point, forcing it to be deposited onto a wafer before other targets are ready.

6.5 Dry Etching

Etching is the process where removal of the substrate takes place where it is not covered by a mask. There are many different types of etching that can primarily be placed in two categories: wet and dry etching. Wet etching involves a chemical bath where a wafer is placed and a chemical reaction takes place to remove the desired material. This type of etching is isotropic and is inappropriate for the purpose of my experiment. Dry etching, on the other hand, can be very anisotropic, allowing for vertical walls to be formed in the desired locations on the chip. [42, 45, 46] There are many dry etching techniques that use a wide range of pressures and excitation energies. They can further be divided into 3 categories; utilizing physical, chemical, or a combination of physical and chemical processes to perform etching. [45]

In the physical process of etching, such as glow discharge sputtering or ion milling, RF excitation is used to energize ions and bombard the surface of the wafer in a strongly directional
Noble gas ions, such as $\text{Ar}^+$, are used to physically knock atoms off the surface of the samples. They remove layers of the material in a very directional way, allowing for strictly vertical walls to be formed around the edges of the masked material. Unfortunately, this type of etching is not selective and all materials are etched, including the metal mask that guides the features of the device. This etching happens at different rates for different materials, but most rates are within a factor of 3 of each other. This means that at most 3 times the thickness of the mask can be etched into the surface of the wafer before complete degradation of the masking material takes place. In addition, a major problem with this type of etching is that the material ejected by the energized ions is most frequently non-volatile and is frequently redeposited onto a wafer and the side walls of the etched features. Based on these issues, dry etching methods that are solely based on physical ion bombardment are not widely used for micro- and nanofabrication of devices. [42, 45, 46]

In the case of strictly chemical mechanism of etching, various gases are used to react with the uncovered substrate, creating a highly selective etch. The process can be broken down into several steps. First, reactive species, such as atoms, radicals, and ions, are generated from the incoming gases by the plasma. They are then transported onto the surface of the sample material by diffusion. After these species are adsorbed on the surface, they chemically react with the material to be etched and create a volatile by-product, which is desorbed by the surface. Once the product of etch is desorbed, it is released into the bulk of the gas and pumped out from the chamber. For this process, mask material selection is very important and, if chosen correctly, will not react with the etching gas preserving the quality of the mask. The etching gas is selected to react chemically with the surface of the wafer and produce a reaction product that is volatile.
This is crucial to the process, since many species can react with the surface. However, unless they are desorbed by the surface of the wafer, no etching can take place. While this process provides high etching selectivity, its etching characteristic is highly isotropic. Vertical etch cannot be produced here. Instead, an undercut of the features is created, which limits the depth achieved by etching. It is uncommon to see purely chemical dry etching performed on the devices that require features smaller than 1 micron. \[45, 46, 47\]

Most present day dry etching tools utilize both chemical and physical based techniques to produce anisotropic and selective etch. While these processes still possess the shortcomings of each method, when the right balance is achieved, they can produce vertical walls with limited mask degradation and minimized undercut. In many cases, the physical ion bombardment aids chemical etching by accelerating desorption of the chemical by-product.

Reactive Ion Etching (RIE) combines chemical and physical processes during etching. Plasma systems are used to ionize reactive gases and direct them towards the surface of the wafer. Ions are then both reacting with the surface of the material to be etched and transferring momentum to create a highly physical reaction. In present experiment, oxygen ions were used to descum the surface of the wafer. While oxygen reacts with the two types of resist used in the lithographic process, it does not react with GaAs. This allows for a highly selective etch of the resist and insures that there is no residual resist left where the metal mask features are to be deposited.

While RIE uses chemically reactive gasses to create both the physical and chemical etching, most plasma systems (including the one used in this experiment) use both reactive and
noble gases to maximize the quality of etching. The ratio of these two types of ions can be adjusted giving high level of control over the resultant etching.

6.6 Experimental Progress

During my experimental attempt to fabricate micropost cavities, I encountered several issues described in this section. The process is very tool and environment specific and needs to be adjusted to retrofit the specific conditions provided by nanofabrication facilities.

In the lithographic process several issues arose while attempting to imprint the surface of the wafer. Two resists are used, primarily to create an undercut in the lower layer, preventing the evaporated metal from sticking to the sides of the walls and interfering with the liftoff process. While working on the deposition of LOR-3A, I find that the resist is very sensitive to changes in the baking procedure. If a wafer is allowed to cool down after a dehydration step before LOR is deposited, the resist is very viscous and forms very thick coating around the edges of the chip. As a result, during a postbake process it does not dry properly, forming large air bubbles around the perimeter of the chip, as seen in Figure 6.1. The prebake process not only insures that the chip is properly prepared for the film deposition, but also aids heating of the resist (that is routinely refrigerated while it is being stored).

A major source of lithographic defects comes from the alignment and development issues. It is important to inspect the samples before exposure for any visible particles that can prevent contact between a sample and a mask. Otherwise, UV rays diffract around the features on the mask, compromising the imprinted pattern. In addition, it is important to calibrate the light source before every use to ensure a correct dose of UV exposure. When the dose is too
**Figure 6.1** Optical microscope images of the GaAs chip edge coated with LOR-3A chemical resist. The sample was allowed to cool before film deposition forming thick edges that bubbled up during a postbake process.
low, it can be insufficient to cause a reaction in the resist. However, when the dose is too high, the film at the boundaries of the mask gets saturated, causing resist to react and misshape the desired pattern. In the case of micropost pillars, the diameter of the resultant circles imprinted in the resist decreases dramatically, causing the smallest features (up to 1.5 microns) to disappear altogether, which can be seen in Figure 6.2.

During the development process, UV activated resist is washed away from the sample in a chemical bath. If the amount of liquid in the bath is insufficient, the solution saturates and gets redeposited onto the surface of the GaAs substrate, as can be seen in Figure 6.3. This can be prevented by ensuring a sufficient amount of the developer is used, combined with agitation of the liquid during the developing process. Once all of the lithographic processes are optimized, a pattern resembling the imprinting mask is seen in the resist, as seen in Figure 6.4.

If the undercut of the chemical resist is not sufficient, the metal deposited on the GaAs substrate through the holes in the resist will still be connected to the metal on top of the resist. As a result, there may be cracks and misshapen features remaining on the substrate after the liftoff process. During my first attempts to liftoff the metal, I ended up with dark rings of unknown composition around the metal masks on the GaAs surface, as seen in Figure 6.5. In attempt to dispose of these rings, I placed the sample in an ultrasonic bath. However, due to stress, the metal masks were shaken off along with the surrounded rings, as seen in Figure 6.6. As a solution, I adjusted the development time of the sample in an attempt to prolong the anisotropic etch of the chemical resist and enlarge the undercut of the film. Overdevelopment of the sample does result in the chemical resist being dissolved and all imprinted features being lifted off, so the sample needs to be watched carefully while in the solution. When features show
Figure 6.2 Optical microscope image of overexposed resist. One micron features in the resist are dissolved during development process.
Figure 6.3. Optical microscope image of the 5 micron features imprinted in the bi-layer resist. During the development process, the chemical bath gets saturated and the lifted resist is redeposited onto the surface.
Figure 6.4. Bi-layer resist film deposited onto GaAs substrate and imprinted with features ranging from 1 to 20 microns. The darker circles are windows cut through the resist, showing GaAs substrate.
up on the substrate, the sample is checked under a microscope to determine if it requires further development.

A descumming process is added here to increase adhesion of the metal layer. The sample is placed in the RIE tool and hit with oxygen plasma for 2 minutes. The total thickness of the second resist (S1813) becomes smaller, but the exposed surface of GaAs is cleaned from any residual resist. Also, the isotropic etch component of the RIE further increases undercut. Since the total thickness of resist is smaller, the thickness of the metal that can be deposited also decreases. However, this insures higher level of adhesion to the surface of the substrate. The final result of the hard mask deposition can be seen in Figure 6.7.

During the metal lift off process, if the thickness of the chemical resist is not sufficient, the isolation of the holes in the hard mask from the remaining metal is not possible. Once I start increasing the thickness of metal I reach a point where the metal could no longer be lifted off. To avoid a switch to a different resist, I experimented with the spinning parameters for the LOR3A resist. While decreasing the spinning speed from 600 rpm down to 200 rpm in steps of 100, I found that a speed of 200 rpm caused a higher level of edge beading, thus making more of the sample unusable after the edge bead removal. 300 rpm speed provided a sufficient increase in the thickness of the resist while decreasing the area of the sample where the film is too thick and has to be removed.

In the etching process, the maximum attainable etch depth is limited by erosion of the Ni mask during the etch. I use several metals for the hard mask on the surface: Ni, Au, and Al. These metals are chosen based on evidence in literature that they adhere to the surface of GaAs. However, Au and Al prove to be more reactive with Cl based plasma etch than Ni and produce...
Figure 6.5. Due to insufficient undercut the liftoff process was not effective in removing all of the resist and residual metal off the surface.
Figure 6.6. Residual resist under the deposited metal pads cause them to detach from the substrate during the liftoff process. Image taken with an optical microscope.
Figure 6.7. Final result of metal deposition and liftoff modifications. Ni circular pads deposited on GaAs substrate to serve as a hard mask for the etch. Image taken with an optical microscope.
very shallow etch in GaAs before being degrading. To solve the problem of the shallow etching I increase the layer of the deposited Ni by adjusting the parameters of the resist spin, allowing for deposition of 160 nm of Ni compared to previous 90 nm.

As it is previously mentioned, during E-beam metal evaporation contamination of the source can play a large part in device fabrication failure. As a result of regular use of the evaporation chamber for different materials, a combination of films settles onto the surfaces of the evaporator. If the chamber is not cleaned correctly, these materials can contaminate the crucibles and create an unknown alloy that can have significantly different properties when etched. Figure 6.8 shows an example of such etching. The masking material shows brittle nature and is flaking off gradually around the edges of the feature. The newly exposed substrate is bombarded by the incoming ions and is etched. As the metal alloy flakes off further, it creates a cone shaped etched feature.

During my experimentation with the parameters of plasma etching, I attempt several values for the reactive to noble gasses ratios. Since erosion of the Ni mask is a major issue during a deep etching, it is important to incorporate chemically reactant gasses such as Cl and BCl3 into the etching parameters. However, etching with high concentration of Cl created a very isotropic etch, causing the sides of the post to degrade, Figure 6.9. Since Cl does not interact with Ni strongly, at the end of this process, one can still see a very thin largely intact film of Ni still attached to the top of the pillar. The sides of the posts also do not exhibit a smooth profile, making apparent the difficulty of utilizing a purely chemical etch.
Figure 6.8. Slow degradation of the edges of the mask due to ion bombardment cause cone shape of the etch.
Figure 6.9. Cl based etching. This process is very selective, creating a deep etch of GaAs relative to Ni. Since Cl does not react with Ni strongly, it primarily etched the GaAs substrate. The etch was very isotropic, reacting with the sides of the posts. The thin film of Ni that was left behind can still be seen at the top of the micropost.
When I introduce a high concentration of Ar into the plasma, it aids in ion bombardment that is highly anisotropic creating a very “clean” vertical etch. However, ion bombardment is not selective, etching the metal mask at nearly the same rate as the substrate. This etch rate was different for the materials used for the mask, proving Au and Al to be unusable for this process. As a result a layer of metal gets etched away early in the process and $\text{Ar}^+$ ions continue bombarding the surface of the substrate, creating deep cavities inside the post. Figure 5 shows a micropost that still has a layer of Ni attached to the surface and one that has been damaged by the continued $\text{Ar}^+$ bombardment. In both cases, the walls of the fabricated posts show damage from the etching process. The nature of these trenches indicates that the concentration of $\text{Cl}^+$ is still too high and needs to be adjusted.

In addition to finding the correct concentration of gasses to create a clean largely anisotropic etch that did not severely degrade the mask, I also have to ensure the level of undercut created by ion bombardment is manageable. Figure 6.11 shows a 1.2 micron diameter post that displays a significant undercut. Reducing the level of $\text{Cl}^+$ and $\text{BCl}_3^+$ further is necessary to reduce it.

After several experimental attempts, I find the 14-9-1 ratio of Ar-$\text{BCl}_3$-$\text{Cl}_2$ acceptable to provide a balance of the two types of processes. Another parameter that is influential in this type of etching is the pressure of the chamber. Lower pressure in the chamber leads to lower momentum of the bombarding ions causing fewer collisions between ions to take place and preventing more radicals to form. The bombardment becomes more directional, accelerating towards the surface of the sample and making the process more physical. Figure 6.12 shows etched micropost when the pressure of the chamber is lowered to 2 mTorr. The rate of etching slows down significantly, down to 2 microns/hour and there are signs of etching taking place.
Figure 6.10. Mask degradation causes the edges of Ni plates to chip off during the etching process. This creates holes in the sides and inside of the micropost.
Figure 6.11. Small diameter of the post makes the undercut more evident.
under the surface of the Ni mask. In addition, lower momentum of the ions does not aid in desorption of the by-product of chemical reaction between Cl\(^+\) and GaAs atoms; they are redeposited on the surface of the wafer. On the other hand, pressures as high as 6-8 mTorr produced an etching too chemical that damaged the surface of the sample and the resultant features. 4 mTorr was necessary for my process to produce better quality devices.

The most current result of this work can be seen in Figure 6.13. Depositing a thicker layer of metal and cooling the chuck to prevent overheating of the sample ensured the reliability of the mask for etching up to 8 microns. Reduction of Cl and BCl3 components and increasing Ar presence in the chamber decreased the damage done to the sides of the post walls and produces anisotropic etch with minimal undercut. Figure 6.14 shows etched GaAs and AlGaAs dielectric Bragg reflector (DBR) stacks.

6.7 Summary

In this Chapter, I present my work fabricating micropost cavities to improve upon work described in Chapter 5. I optimize lithographic processes, metal deposition, and etching techniques to etch GaAs and AlGaAs dielectric stacks. I describe the issues that arise when implementing this work and ways to resolve them. During my progress, I am able to eliminate defects such as insufficient adhesion of masking metal to the surface of the substrate, damaged side walls of microposts, rapid degradation of the hard mask, as well as isotropic etching profile.

Future work includes fabricating microposts with appropriate samples of DBR stacks with enclosed quantum dot cavities and repeating the experiment described in Chapter 5.
Figure 6.12. Low pressure in the chamber slows etching and morphs the mask.
Figure 6.13. Final etching result of GaAs substrate. Concentrations of gasses, chamber temperature and pressure were adjusted to ensure minimal damage to the side walls of the posts, clean substrate surface, and minimal mask degradation.
Figure 6.14. Etching with Ar/BCl3/Cl2 of the DBR structure with GaAs and AlGaAs stacks.
CHAPTER VII

CONCLUSIONS

The HOM interferometer has proven to be a valuable research tool in the field of quantum optics. One of the great properties of this interferometer is a quantitative measurement of distinguishability of single photons. In addition, it can be used as a super sensitive sensor that uses quantum effects to measure various classical properties (group velocity, refractive index change, etc.) Many of the properties of an HOM interferometers have been described to date, however its full potential is not fully understood yet.

In my thesis research I aim at reaching a deeper understanding of HOM sensors and information that can be extracted from HOM measurements. In Chapter 3 I describe a completed project where an HOM timer was used to determine propagation delay differences with sub-femtosecond accuracy. The abnormalities of light propagation through dielectric stacks of various compositions are investigated. Because of HOMs sub-femtosecond sensitivity, I experimentally find that structures with very similar composition can give rise to both superluminal and subluminal propagation delays. Addition of single layers to any stack structure causes a fluctuation of traversal times, which is very counterintuitive. Finally, with further addition of layers, the propagation delays saturate, becoming increasingly superluminal.

In Chapter 4 I describe a theoretical study that further expands the capabilities of an HOM sensor. By measuring the changes in visibility of an HOM dip, one can determine whether one of the photons has been distorted as a result of barrier propagation. I demonstrate that one can directly measure the amount of wavepacket distortion of a single photon that took place as a result of its propagating through a medium. I use this model to further analyze the results of
study in Chapter 2. This allows to put a limit on total distortion of signal photon spectral function as a result of dielectric stack traversal.

In Chapter 5, I combine the experience on SPDC and HOM properties and apply it to a project where the two single photon sources of different nature are forced to produce photons that are indistinguishable from one another. That is, in the language of quantum mechanics, no measurement can disclose which source produced a give photon, even in principle. For this purpose I use photons generated by SPDC and QD. I demonstrate partial coalescence, that points to partial indistinguishability, limited only by the decoherence in the QD. Since decoherence of QD is the main reason of reduction in coalescence, and there are techniques to drastically limit decoherence impact on a QD, one can extend my experiment to demonstrate higher levels of indistinguishability, particularly these allowing entanglement between such sources.

In Chapter 6, I attempt to improve the degree of coalescence measured in the previous chapter by improving the emission of one of the semiconductor quantum dot sources. By creating a microcavity around a layer of quantum dots, one can create a confinement and decrease the amount of thermodynamically irreversible interactions for the single photon produced as a result of quantum dot emission.

As a result of my thesis research, I present a better understanding of measurements done with a HOM sensor, and apply it to engineer single photon sources that can be used for cross-platform entanglement. This research benefits the field of quantum information, allowing for establishment of scalable quantum networks comprised of sub-systems of different nature.
APPENDIX

Fabrication Steps for Micropost Cavities.

1. The sample of GaAs substrate is cleaned in Acetone for 5 minutes and Isopropyl Alcohol for 3 minutes and nitrogen dried.

2. The sample gets prebaked at 200C for 10 minutes.

3. A layer of Microchem LOR 3A resist is spun on the sample at 3000 rpm for 40 seconds. It is necessary for the sample to still be hot before the chemical resist gets deposited. Otherwise, the resist does not get distributed evenly and it forms bubbles on the surface during the postbake.

4. The sample is post-baked at 130C for 5 minutes. After the post-bake the sample is inspected for visible bubbles and dirt particles. If anything is present on the surface, the sample gets cleaned in the developer for 10 minutes and steps 1-4 get repeated.

5. Shipley Microposit series S1813 is spun onto the GaAs substrate at 4000 rpm for 40 seconds.

6. The sample is post-baked for 1 minute at 130C. Once again, the sample is inspected for visible specks and bubbles. If they are found, the sample gets exposed to UV light and soaked in developer for 10 minutes. Steps 1-5 are repeated.

7. The thick edges around the sample have to be removed to ensure contact with the mask. The sample is loaded onto a chuck and an aluminum foil mask is used to isolate the edges to be removed, which get exposed using the flood exposure setting. All edges get exposed one by one.
8. The sample is soaked in a developer for 2 minutes and bathed in water to terminate the developing process. It is then nitrogen dried.

9. The UV lamp gets calibrated and the correct exposure time is calculated based on the power of the source.

10. The sample is exposed in a UV lithography system for the second time. It is loaded onto the chuck and the mask is inserted on top of it. The mask and the sample are brought into contact. A camera is used to align the mask with the sample. Since the sample is close to 1 cm x 1 cm, it is important to use the correct part of the mask.

11. The sample is then developed in a developer MF319. Here it is important to stir the developer to avoid the residual resist settling back onto the sample. It is also crucial not to overdevelop the sample, since it increases undercut under the photoresist layer and may result in all of the resist getting washed away. If the sample is underdeveloped, the features will not show up in the resist or the undercut will be insufficient for a successful metal liftoff. If all is done correctly, the result is a pattern of small holes in the resist with an undercut in the chemical resist layer. The sample is bathed in water to stop the developing process and nitrogen dried.

12. The sample is inspected under an optical microscope to ensure the quality of the features.

13. The sample gets processed in RIE system for 2 minutes to clean the surface and etch away remainder of resist.

14. A thin layer of Ni is then evaporated onto the sample.

15. The remaining resist is dissolved in a solvent, so that the metal above it is lifted off.
16. The resulting pattern of small metal pads is used as a mask for an anisotropic dry etch. In this way, posts with diameters from 1.5 to 20 µm can be etched into the sample. Graphic representation of these processes can be seen in Figure A1.
Figure A1. Fabrication diagram for micropost cavities. a-c) Deposition of chemical and photo resists; d) edge bead removal; e) exposure and development of photoresist; f) anisotropic development of chemical resist creating an undercut; g) descumming process; h) metal deposition; i) liftoff process; j) plasma etch.


