Quantum interferences with nanostructured metamaterials

Altuzarra, Charles

2018

Altuzarra, C. (2018). Quantum interferences with nanostructured metamaterials. Doctoral thesis, Nanyang Technological University, Singapore.

<http://hdl.handle.net/10356/73272>

<https://doi.org/10.32657/10356/73272>

**NANYANG
TECHNOLOGICAL
UNIVERSITY**
SINGAPORE

Quantum Interferences with Nanostructured Metamaterials

Charles Altuzarra

ALTUZARRA, CHARLES

School of Electrical and Electronic Engineering

A thesis submitted to the Nanyang Technological University
in fulfillment of the requirement for the degree of
Doctor of Philosophy

2017

“The main object of physical science is not the provision of pictures, but is the formulation of laws governing phenomena and the application of these laws to the discovery of a new phenomena.

If a picture exists, so much the better; but whether a picture exists or not is a matter of only secondary importance.”

- Paul A. M. Dirac (1958)

Acknowledgments

A very special thanks goes to Dr. Stefano Vezzoli for having been a true mentor through his teachings of experimental and theoretical quantum optics, for enduring the pain of aligning a polarization entangled photon setup with me until the late hours of the night and most of all, for your friendship.

I further would like to thank my supervisors, Profs Cesare Soci and Christophe Couteau for guiding me through my doctoral degree. In addition I would like to thank the directors of CINTRA, Prof Philippe Coquet and particularly Prof Dominique Baillargeat for his efforts related to acquiring a scholarship. On that note, I would like to thank NTU, NUS and A* Star for their SINGA scholarship.

A special thanks goes to the director of CDPT, Prof Nikolay Zheludev, for providing the financial means to conduct all the experiments. Further, I am exceedingly thankful for the numerous scientific discussions, without which my understanding of the highly significant field of nanostructured metamaterials would not be where it is today.

I would like to thank Dr. Giorgio Adamo for his helpful insights on all things related to nanofabrication. By the same token, I am indebted to Hou Shun Poh and Christian Kurtsiefer for their invaluable experimental input in building the SPDC polarization entangled source. I would also like to thank ‘the night shift’ comprised of Dr. Guanghui Yuan, Prof. Liyong Jiang, Jiaying Liang, also ‘the day shift’ with Eng Aik Chan, Dr. Hailong Liu, Dr. Venkatram Nalla, Dr. Alexander Dubrovkin, Dr. Yasaman Kiasat, Dr. Harish Krishnamoorthy, and ‘the nightly day shift’, Syed Aljunied, for our scientific conversations and our much cherished friendships. I add that I especially thank Venkatram and Syed for being my lifeboat and answering my overwhelmingly large amount of questions.

6 Acknowledgments

I also extend my thanks to several colleagues from CINTRA which include Ange Maurice, Umar Saleem, Etienne Rodriguez, Dr. Christophe Brun, Dr. Aurelien Olivier and of course my very esteemed friend Dr. Christophe Wilhelm. Likewise, I would like to thank Yin Jun, Daniele Cortecchia, Dai Xing, Paola Lova and especially Xin Yu for their friendships and support.

I am also immensely grateful for having been blessed with one of the best collaborators anyone could ask for, Dr. Joao Valente. I am also indebted to Abdul Rahman Bin Sulaiman for training me in using the CNC, vertical drilling, hydraulic shearing, and hydraulic bending machines.

In a slightly unconventional manner, I would like to express my appreciation to the following musicians for creating tracks that kept me going in hard times: 'the weeknd', 'Frank Sinatra', 'Jay-Z', 'Compay Segundo', 'Miles Davis' and 'Group Therapy weekly mixes with Above and Beyond'.

Most importantly, I am immensely grateful to my parents for their guidance and support, and for never failing to point out the constant and imperative need for me to get a haircut and shave.

Table of Contents

Acknowledgments5

Table of Contents7

Summary..... 11

List of Figures..... 13

List of Tables 18

Chapter 1 - Introduction 19

 1.1 - Motivation..... 19

 1.2 - Objective22

 1.3 - Major Contributions of the Thesis23

 1.4 - Organization of the Thesis23

Chapter 2 - Fundamental Concepts25

 2.1 - Introduction.....25

 2.2 - Quantum Sources.....26

 2.2.1 - The Heralded Single Photon Source26

 2.2.2 - The Polarization Entangled Photon Source28

 2.2.2.1 - Theory28

 2.2.2.2 - Optical Setup/Alignment.....34

 2.3 - Fabrication and Characterization Processes.....41

 2.3.1 - Software Simulations with COMSOL41

 2.3.2 - The Fabrication Hardware42

 2.3.3 - The Characterization Hardware.....43

Chapter 3 - Quantum Coherent Perfect Absorption...	45
3.1 - Introduction.....	45
3.2 - Coherent Perfect Absorption of a Single Photon	52
3.2.1 - The Plasmonic Metamaterial.....	53
3.2.2 - The Optical Apparatus.....	54
3.2.3 - The Results	56
3.3 - Coherent Perfect Absorption with Entangled Photon Pairs.....	58
3.3.1 - The Concept	59
3.3.2 - The Quantum Eraser	59
3.3.3 - Fabricating the Plasmonic Metamaterial.....	63
3.3.4 - The Quantum Eraser Interferometer Optical Apparatus	73
3.3.5 - The Local Quantum Eraser CPA.....	76
3.3.5.1 - The Theory	76
3.3.5.2 - The Experiment and the Results	83
3.3.6 - Nonlocal Coherent Perfect Absorption	87
3.3.6.1 - The Theory	88
3.3.6.2 - The Experiment and the Results	91
 Chapter 4 - Super-oscillation of a Single Photon	 97
4.1 - Quantum Super-oscillation	97
4.2 - The Concept.....	101
4.3 - The Experiment.....	102
4.4 - The Results	105
 Chapter 5 - Conclusions and Recommendations	 109
5.1 - The Conclusion.....	109
5.2 - Recommendations for Further Research	110
5.2.1 - EPR States Nonlocal Measurements with Plasmonic Slits	110
5.2.2 - CPA for polarization rotation	113

Appendix 119

Bibliography 125

Author’s Publications 131

Summary

The subject of this thesis is focused on the investigation of interactions between quantum states of light and nanostructured metamaterials. Hence, producing the results shown within this manuscript required both an expertise in quantum optical alignments and nanofabrication of metamaterials.

To be more specific, the acquired expertise in quantum optical alignment was portrayed by building a heralded single photon source, which is a source for which at one point in space along the optical path there is only one photon at a time. In addition, an alignment of higher complexity was conducted to obtain an entangled photon pair source for which two photons of a pair may be separated in space, but by virtue of measuring the polarization state one of the photons of the pair, the polarization state of the other photon is defined ‘nonlocally’.

Fabricating the metamaterials constitutes the other type of expertise acquired during this thesis. Nanofabrication is made possible through different techniques which either have to do with adding material or removing material from a substrate. Moreover, part of the fabrication process requires numerical simulations and optical characterizations of nanostructures.

Once the quantum sources were built and the metamaterials were fabricated, we studied how single photons in the form of waves can interfere in optical interferometers in such a way to be fully absorbed by plasmonic metamaterials. In a similar manner, we compared the absorption properties of non-interfering single photon particles with the absorption properties of interfering single photon waves. These results were produced by virtue of pre-selective and post-selective measurements for a quantum eraser interferometer.

12 Summary

And, by extension, the first quantum ultrathin metamaterial ‘flat-lens’ for single photons is demonstrated in the form of a ‘Young’s N-slit’ experiment. The results show that we super-oscillate a single photon to focus past the Abbe diffraction-limit.

List of Figures

Figure 2.1 - Illustration of a $g^{(2)}(0)$ measurement whereby the beamsplitter BS creates two optical paths to the coincidence module.....	27
Figure 2.2 - Illustration of ‘typical’ spontaneous parametric down-conversion optical setup. Two single photon paths are created, idler and signal. P_{idler} and P_{signal} are two polarizers.	29
Figure 2.3 - Visibility curves for $V_{H/V}$ (dashed line with red circular markers) and $V_{-45/+45}$ (solid curve with purple circular markers).....	33
Figure 2.4 - Diagram of the 2D imaging scanner. A labview program sends commands to the linear stage motors. At each position of the linear stages, single and/or coincidence counts are recorded onto the labview program.	35
Figure 2.5 - Imaging the generation of SPDC cones for different tilts of the BBO relative to the incident pump beam with the 2DIS.	35
Figure 2.6 - Alignment of the right angle mirrors (RAMs). (c) and (d) are the imaged intersections without the pinholes for paths I and II respectively. (b) and (e) are the imaged intersections with the pinholes for paths I and II respectively.	36
Figure 2.7 - (a)-(d) 2DIS scans of the intersections for different positions of the collimating lens (CL) placed in between the two pinholes (PH) in both paths in the optical setup shown in (e).	37
Figure 2.8 - Final optical setup with the half-wave plates (HWP) and compensating BBO crystals (CC).....	38
Figure 2.9 - Compensation crystal profiles for a rotation change and a tilting change of the configuration relative to the input pump beam.	39

Figure 2.10 - On the left, the scan for the 2mm thick BBO, on the right, one of the scan for the 1mm thick BBOs.....	40
Figure 2.11 - The single photon scan in the bottom left frame is compared with the coincidence counts in the bottom right frame and top left frame for the y and x coordinates respectively.....	40
Figure 2.12 – Ordered steps for producing the metamaterials.....	41
Figure 3.1 - Illustration of two single mode fibers joined by a two channel resonator where two beams, Beams A and B, are counter propagating and for which the reflection of one beam interferes with the transmission of the other beam, and vice versa.....	46
Figure 3.2 - Coherent control with standing waves. On the left, coherent perfect transmission, on the right, coherent perfect absorption.....	48
Figure 3.3 - Absorption modulation – Metamaterial (red curve) vs. unstructured gold (blue curve).....	49
Figure 3.4 - Representation of the optical scheme used in Huang and Agarwal's work on theory of CPA with path entangled single photons. The input single photons are incident on a beamsplitter BS. Two optical paths $a_{in}(\omega)$ and $b_{in}(\omega)$ are generated of lengths l_1 and l_2 respectively. The single photon reflects, transmits or is absorbed at a medium. The outputs are collected, denoted $a_{out}(\omega)$ and $b_{out}(\omega)$	51
Figure 3.5 - (a) SEM image of the plasmonic nanostructured array for which the optical properties are measured in (b).....	54
Figure 3.6 - Results from the $g^{(2)}(0)$ measurement produced from the SPDC source.....	55
Figure 3.7 - Illustration of the optical setup used for demonstrating coherent perfect absorption of a single photon.....	55
Figure 3.8 - Heralded photon counts (a) for output γ normalized to input α , (b) for output δ normalized to input β , (c) averaged normalized counts of γ and δ	

and (d) for a 30-layer chemical vapor deposition-grown graphene film as a function of the sample position..... 57

Figure 3.9 - Simple representation of a Mach-Zehnder quantum eraser. 61

Figure 3.10 - Low quality 50nm dry-etched Gold freestanding membranes displaying stretching. 64

Figure 3.11 - Map of a nanostructured high quality membrane (a) and in (b) zoom in of the lower right quadrant of the membrane. Framed in the short-dashed green line is the structure used for the experiment (SR5), framed in the dotted white line are the focusing calibrating $5\mu\text{m} \times 5\mu\text{m}$ structured arrays, and framed in the long-dashed red line is structure SR8 used for comparisons..... 65

Figure 3.12 - (a) SEM image from a low quality focusing regime with FIB and in (b) SEM image from a high quality focusing regime with FIB. 66

Figure 3.13 - The SR5 preferred structure's reflection (orange), transmission (blue) and absorption (green) spectra produced with the microspectrophotometer for the horizontal polarization (solid line), the vertical polarization (dashed line) and the +45 polarization (dotted line). The red vertical line represents the 810nm wavelength of our photons. The noise observed at 900nm are due to the switch of detectors in our microspectrophotometer. 68

Figure 3.14 - Structure SR5 comparison of optical properties for light incident from opposite sides of the sample. The reflection is denoted by the orange curves, the transmission is denoted by the blue curves and the absorption is denoted by the green curves for horizontally polarized light (left), vertically polarized light (middle) and 45 degree polarized light (right). The red vertical line designates the 810nm wavelength of our photons. The noise observed at 900nm are due to the switch of detectors in our spectrometer. 69

Figure 3.15 - Structure SR8 from the gold side. The reflection is denoted by the orange curves, the transmission is denoted by the blue curves and the absorption is denoted by the green curves for horizontally polarized light (left), vertically polarized light (middle) and 45 degree polarized light (right). The red vertical line designates the 810nm wavelength of our photons. The noise observed at 900nm are due to the switch of detectors in our spectrometer..... 71

- Figure 3.16** - Polarization variation optical properties. Reflection (orange), transmission (blue) and absorption (green) for different polarization states with a 10 degrees incrementation. **72**
- Figure 3.17** - Illustration of quantum eraser interferometer. Path I from the entangled source is guided to the interferometer with single mode optical fibers. The photons are then collimated through a collimation lens (CL). To compensate for the optical fiber effects on polarization, a combination of a quarter-wave plate (QWP), half-wave plate (HWP), flip mirror (FM) and polarizer (P) are used. The metamaterial is aligned with a 808nm continuous wave laser and imaged with the CCD camera. **74**
- Figure 3.18** - Top left: the coincidence counting module receiving single photon counts from single photon detectors. Coincidences are counted between outputs of interferometer C and D, and the output coupler in path II of the entangled source. **83**
- Figure 3.19** - (a) CPA with: the plasmonic metamaterial (exp:blue hollow circular markers,fit:blue dotted curve); unstructured gold (exp:red hollow diamond markers, fit:solid red line); the metamaterial and HWP A (exp:green hollow square markers fit: solid green line). (b) Local quantum erasing of CPA with polarizers at the output set to the 45 polarization (exp: blue filled circular markers, fit: blue dotted curve), the vertical polarization (exp: red filled diamond markers, fit: solid red line) and the horizontal polarization (exp: green filled square markers, fit: solid green line). **86**
- Figure 3.20** - Top left: the coincidence counting module receiving single photon counts from single photon detectors. Coincidences are recorded between outputs of interferometer C and D, and the output coupler in path II from the SPDC source. **91**
- Figure 3.21** - (a) CPA with nonlocal measurements in H (green squares), V (black diamonds) and +45 (red circles). (b) relevance of entanglement with CPA for a high visibility of entanglement and low visibility of entanglement. **93**
- Figure 3.22** - Visibilities in the crossed-polarization basis for the high entanglement regime used for the experimental results and the low entanglement regime that show a much lower visibility value. **94**
- Figure 4.1** - (a) Young's one slit experiment, (b) Young's two slit experiment, (c) Young's three slit experiment, (d) Young's four slit experiment, (e)

Young's five slit experiment. (a) – (d) have the electron micrograph images of the structures on the left and the camera image of the diffraction patterns on the right..... **98**

Figure 4.2 - Similarities between super-directive antennas illustrated on the left and super-oscillatory lenses, illustrated on the right..... **99**

Figure 4.3 - Labeled graph showing the field of view, the hotspot width and sideband. **100**

Figure 4.4 - (a) Interference fringes for a Young two-slit experiment. (b), tailored interference of super-oscillatory lens..... **101**

Figure 4.5 - SEM image of the fabricated meta-lens, and definition of |H and |V polarizations..... **102**

Figure 4.6 - Illustration of the optical setup for the $g^{(2)}(0)$ measurement. **102**

Figure 4.7- Optical setup for the superoscillation of a single photon experiment. The SPDC source to the right generates single photon pairs at the BBO crystal. One of the photons of the pair is counted in coincidence via a single photon counter. The other photon is transmitted through the sample and ends up being collected at the 'collection SMF' **103**

Figure 4.8 - (a) Imaging the map of all structures to align different structures, (b) imaging of a single SOL, (c) imaging of the hotspot and sidebands. **105**

Figure 4.9- Super-oscillatory hotspot of a single photon for (a) the horizontal polarization |H and (b) the vertical polarization |V. **106**

Figure 4.10 - Comparison of analytical calculations, FDTD simulations and the classical measurement for the horizontal polarization and vertical polarization. **107**

Figure 5.1 - Proposed optical setup where one of the photons of the pairs (left) goes to the CPA interferometer while the other photon of the pairs (right) is measured with the plasmonic slit nanostructure. **111**

Figure 5.2 - On the right, the SEM image of the plasmonic slits. On the left, the Bell measurement in the horizontal-vertical polarization basis..... **112**

Figure 5.3 - Bell measurement with plasmonic slits in the horizontal-vertical polarization basis. **112**

Figure 5.4 - (a) Resonance in reflection as a function of an incident x polarization. (b) Resonance in reflection as a function of an incident y polarization. (c) parameters of the unit cell of the silver metamaterial array. (d) dependence of the coupling regime on the gap..... **114**

Figure 5.5 - SEM images: (a) Metamaterial membrane with the array centered, (b) overview of a part of the array, (c) closeup of the unit cells..... **115**

List of Tables

Table 1 - structure SR5 values for 810nm optical reflection, transmission and absorption for the horizontal polarization H, the vertical polarization V and the 45 degree polarization 45°. **67**

Table 2 - Structure SR8 values for 810nm optical reflection, transmission and absorption for the horizontal polarization H, the vertical polarization V and the 45 degree polarization 45°. **70**

Chapter 1

Introduction

1.1 - Motivation

One gas flame, one needle, several smoked glass screens and five photographic films was the list of components needed in 1909 when Sir Geoffrey Ingram Taylor was the first to produce experimental results that hinted to the interference of a single photon [1]. He recreated a ‘Young’s two slit experiment’ with a light source that consisted of a ‘gas flame’ for which light transmitted through a slit incident on a needle. As a result, the needle’s shadows produced fringe-like patterns due to interfering optical paths. By virtue of placing different attenuating smoked glass screens in the path of the source, the fringes were recorded for five different intensities on different absorptive photographic films. Through a process of comparisons, he noticed the fringe patterns were equivalent for all films and no films showed the absence of fringes. In other words, even extremely low levels of light produced interferences. It is worth mentioning that the light source could not have been in a single photon regime due to the fact that the light generated from the gas flame was incoherent as was aptly pointed by Alain Aspect [2]. Hence, Sir Taylor was not responsible for the first demonstration of the wave-particle duality but his experiment is still referred as having highly impacted the scientific community.

A bit more than a decade later, Louis De Broglie formulated a theory in which he suggested that similar to light, matter should also display wave-particle duality. Then, unintentionally, in 1927 De Broglie's theory was experimentally proven by Davisson and Germer [3] through the observation of constructive interference of directional scattering of electrons on a crystalline nickel surface. As an extension, in 1961, the first demonstration of the electron's wave-particle duality for Young's slit experiment was established [4]. For that experiment the greatest challenge was specific to efficiently detecting the interference fringes. The problem originated from the extremely short wavelength of electrons, which meant that the diffraction slits needed to be very narrow. Thus, Claus Jönsson fabricated five 300nm wide slits separated by a gap of 1 μ m on a 20nm thick layer of silver. Incidentally, other physical effects that have to do with the relationship between slit size and wavelength developed into a field for which matter is used to control light.

Structurally engineering materials to produce specific optical properties which are unattainable by their natural state has been defined as metamaterials [5, 6]. More specifically, a material's behavior when interacting with an electromagnetic field is dictated by its characteristic effective permittivity (ϵ_{eff}) and permeability (μ_{eff}). On that account, it follows that a tuning of these effective parameters, which takes place by redefining the framework of the material, is equivalent to tailoring the electromagnetic field response. Practically speaking, this resonance effect is created as a result of fabricating subwavelength structures for which their size is highly dependent on wavelength of the incident optical field.

Further to my previous statements, an electromagnetic field interacting with either a metallic metamaterial or a dielectric metamaterial may be described in the same manner except for metallic resonating plasmonic metamaterials. In that case, the electromagnetic wave frequency is coupling with the frequency of oscillation of electrons on the metallic surface. The collective oscillations of electrons are called surface plasmon polaritons (SPP). When light is absorbed into plasmons, the energy is converted into heat and scattered outward as thermal

energy [7]. Further, light may also back-scatter in reflection or scatter forward through the metallic surface in transmission. In addition, for particular parameters of a plasmonic nanohole array, results have shown that a greater transmission of classical waves can be produced as compared to non-plasmonic metamaterials.

The newly observed “extraordinary optical transmission” (EOT) [8] was discussed at great lengths with respect to interferences of plasmon modes [9]. Thus, with regards to the previously highlighted parallel between the wave-particle duality and interference, Altewischer *et al.* [10] conducted EOT with quantum states of light, namely photons in superposition of polarization states. Furthermore, they demonstrated that in spite of transmitting through the plasmonic nanohole array, the purity of the quantum state remained the same, which is perhaps due to the fact that circular holes will not collapse the superposition of polarization states. These results initiated more fundamental experiments in providing the validation of the wave-particle duality of plasmons.

The first experiment that demonstrated the wave-particle duality of plasmons was produced by Kolesov *et al.* [11]. In this experiment NV-center nanodiamonds were deposited onto silver nanowires. When the ensemble was optically pumped, plasmons were generated and propagated either to one end or to the other of the nanowire. Through cross correlation measurements of single plasmons and detection of plasmon interference at the ends of the nanowire, they demonstrated that plasmons were defined as both particles and waves respectively.

Still within the spectrum of investigating the wave-particle duality with nanostructured materials, Dheur *et al.* [12] observed interference fringes by coupling a fabricated ‘plasmonic beamsplitter’ grating in a mach-zehnder interferometer.

Thus, by backtracking, we deduce that with time there has been a noticeable progression from the early 1900s when research was mostly focused on the foundations of wave-particle duality of photons to more recent times with the study of wave-particle dualities at the interface of metallic materials/metamaterials. Understanding the importance of uncovering the

influence of material properties on quantum states is best highlighted by Claus Jönsson. He showed that without the ability of nanostructuring through advanced techniques in fabrication for the optimization of detection, he would have never been able to uncover such relevant results and to significantly contribute to completing the picture of the wave-particle duality of electrons. On that account, the advancement of the scientific field has substituted Claus Jönsson's need of nanostructures for improving detection efficiency with today's use of nanostructures to provide a medium that conserves and interacts with quantum states of light.

However, out of the rich properties that make the use of metamaterials unique, two particular aspects were unexplored in the quantum regime. 1) thin film absorption of plasmonic metamaterials and 2) the manipulation of wave-particle interferences with nanostructured slits. And hence the motivation of this thesis is constituted by the study of wave-particle duality with metamaterial designs that have the potential to fully absorb and focus a single photon. In this context, four completed experiments are disclosed within the body of this manuscript.

1.2 - Objective

As highlighted in the previous section, the objectives for this thesis is to provide both the theoretical and experimental:

- Conversion of classical coherent absorbers to the quantum regime with heralded single photons in the setting of a Sagnac interferometer.
- Investigations of quantum coherent perfect absorption that depend on nonlocal measurements on polarization entangled photons in a quantum eraser interferometer.
- The development of a quantum super-oscillatory 'flat lens' for heralded single photons.

1.3 - Major Contributions of the Thesis

The major contributions of this thesis are related to the full absorption and manipulation of quantum states of light with metamaterials. To be more specific the work in this thesis contributed to the field of quantum optics and material science through:

- The investigation of coherent perfect absorption of a single photon with subwavelength thin 50nm freestanding metamaterials.
- The fabrication of an asymmetric split-ring array metamaterial on a 50nm thick freestanding thermally evaporated layer of gold for which both horizontal and vertical polarizations have identical absorption coefficients.
- The investigation of a ‘remote control’ of coherent perfect absorption with polarization entangled photons in the setting of a pre-selective and post-selective quantum eraser interferometer. This constituted in building a polarization entangled photon setup, building a quantum eraser interferometer and aligning the fabricated freestanding asymmetric split-ring metamaterial.
- The development of using a ‘Young’s slit’-type metamaterial to focus single photons past the diffraction limit with super-oscillation. This was done by building a heralded single photon source and doing the optical alignment of the metamaterial with the single photons.

1.4 - Organization of the Thesis

This thesis has been organized by first introducing the quantum sources and fabrication methods needed in the comprehension of the next chapters. Due to the fact that the four experiments conducted during my thesis investigate two particular types of quantum interference schemes, they are broken down into two chapters: chapter 3 and chapter 4. And finally, Chapter 5 provides a conclusion with two recommendations for further research.

For the purpose of being more specific, Chapter 2 defines heralded single photon sources and polarization entangled photon sources and illustrates the details relevant to the optical setup. In addition, the techniques and instruments used for the fabrication and characterization of the metamaterials are listed.

Chapter 3 focuses first on defining coherent perfect absorption through a literature review of a) the classical theory, b) two classical experiments and c) the quantum theory. Then the three quantum coherent perfect absorption experiments conducted during my thesis are presented each aligned with quantum formulations.

Chapter 4 defines superoscillation as an introduction before describing the experiment, and discussing the data.

And finally chapter 5 provides a conclusion in relation to the previous results. Moreover, recommendations for future works in the fields of quantum optics and material science are suggested.

Supplementary to these chapters, the references and a list of publications and conferences are at the end of the manuscript. Furthermore, a summary and the list of figures is presented in the pages that precede chapter 1.

Chapter 2

Fundamental Concepts

2.1 - Introduction

As previously underlined, the objective of this thesis falls under the category of combining two very different fields of research together, namely quantum optics and material science. Thus, in order to have a clear comprehension of the experiments presented in chapters 3, 4 and 5, I present here the ‘fundamental concepts’. Two categories constitute this chapter. The first category presents the quantum sources built during my thesis. More specifically, details on the theories, techniques and alignment procedures unique to the heralded single photon sources and the polarization entangled photon source used to create quantum interferences are provided. The second category introduces fundamentals regarding the simulation, fabrication and characterization processes in producing nanostructures.

2.2 - Quantum Sources

2.2.1 - The Heralded Single Photon Source

Various techniques can produce a single photon regime. Single photons have been generated with NV centers [13], quantum dots [14, 15], and atoms [16] to name a few.

In this experiment, single photon pairs are generated by using a nonlinear optical effect called spontaneous parametric down-conversion (SPDC). For this effect, a birefringent crystal is used. In our case a β -Barium Borate (BBO) crystal is pumped by a laser of 405nm in wavelength. The nonlinear effect then generates photon pairs for which energy and momentum is conserved, thus, the wavelength of each photon of the pair, namely idler and signal, are doubled to 810nm. Two types of SPDCs exist which is specific to the polarization of the photon pairs relative to each other. Type-I SPDC creates pairs of the same polarization and type-II SPDC pairs of orthogonal polarizations.

In the presence of SPDC, the generation of single photon pairs is verified with a correlation-detection scheme electronically produced by a ‘coincidence counting module’ purchased from ID Quantique (ID800). This module will register the individual single idler counts from one detector and the single signal counts from the other. If one count at each detector is recorded within a specific ‘coincidence time window’ (generally in the order of 10-20 nanoseconds) by the coincidence counting module, then one pair of photons has been counted. This is of course only true for a coincidence time window which is less than the coherent time of the photons, in other words, less than the separation between two single photons.

When a quantum source in the single photon regime needs to be authenticated, an auto-correlation measurement or $g^{(2)}(0)$ measurement for short has to be conducted. Experimentally, a $g^{(2)}(0)$ measurement is produced by the virtue of a coincidence counting module. As illustrated by the figure below, a 50:50 beamsplitter (BS) is in the optical path of the single photon source. In the case of

a single photon going through the beamsplitter at a time t , the single photon will either transmit through or reflect on the beamsplitter with 50% probability.

Figure 2.1 - Illustration of a $g^{(2)}(0)$ measurement whereby the beamsplitter BS creates two optical paths to the coincidence module.

Thus, a single photon has the possibility of taking two paths, which are depicted in the figure by a dashed line for when it reflects at beamsplitter BS and a dotted line for when it transmits through beamsplitter BS. For a time delay $\tau = 0$, if the dashed line and dotted line are of exactly the same length, then the single photon takes exactly the same amount of time to get from the beamsplitter BS to the coincidence counting module. Hence, this measurement yields no coincidence counts since a single photon only takes one path through the beamsplitter.

But if $\tau > 0$, and a time delay is added onto the dotted line path, then coincidences slowly increase, due to the fact that in this case a transmitted single photon can arrive at the same time as the photon having taken the dashed line right behind it. This will produce a dip where the intensity/coincidence counts at $\tau = 0$ would be zero or close to zero.

On the other hand, if there is more than one photon at a time t , in other words if the source were a multi-photon source, coincidence counts would be nonzero, since several photons arrive at the beamsplitter at once. The visibility, which describes the difference between the minimum and maximum coincidence counts would be very low as well. The lowest coincidence counts in a $g^{(2)}(0)$ measurement validates the single photon regime.

2.2.2 - The Polarization Entangled Photon Source

2.2.2.1 - Theory

Entangled particles was first theoretically demonstrated by Albert Einstein, Boris Podolsky and Nathan Rosen, in their paper which is referred to as the EPR paradox [17]. Years later, Alain Aspect demonstrated experimentally the high nonlocality effects that were described by the theory [18]. Consequently, other experimental techniques for producing entangled states were demonstrated, more specifically a technique that used nonlinear optical crystals to generate polarization entangled photon pairs [19, 20]. The nonlinear effect most frequently used was mentioned previously, namely spontaneous parametric down-conversion (SPDC).

As stated above, there exists two types of spontaneous parametric down-conversions to generate polarization entangled states. Their wavefunctions typically are:

$$\text{Type I:} \quad |\Psi\rangle = \frac{1}{\sqrt{2}} (|H\rangle_i |H\rangle_s + |V\rangle_i |V\rangle_s) \quad [2.1]$$

$$\text{Type II:} \quad |\Psi\rangle = \frac{1}{\sqrt{2}} (|H\rangle_i |V\rangle_s - |V\rangle_i |H\rangle_s) \quad [2.2]$$

Subscripts 'i' and 's' denote the two photons of the pairs, idler and signal respectively. In the simple illustration shown in figure 2.2, a pump laser is generating entangled photon pairs at the center of the thickness of the nonlinear crystal defined by the type II wavefunction in equation 2.2. The idler and signal photons represented by red lines are detected at two different couplers. P_{idler} and P_{signal} are two polarizers placed in the optical paths of the photon pairs used to measure the polarization states of the idler and signal photons respectively. If we place P_{idler} in the path of the idler photons and remove P_{signal} , by what follows from the wavefunction in equation 2.2, making a measurement on the polarization state of the idler photon with either $|H\rangle_i$ or $|V\rangle_i$ will project a specific signal photon polarization state of either $|V\rangle_s$ or $|H\rangle_s$ correspondingly as

demonstrated in the derivations of the probability amplitudes in equations 2.3 and 2.4.

Figure 2.2 - Illustration of ‘typical’ spontaneous parametric down-conversion optical setup. Two single photon paths are created, idler and signal. P_{idler} and P_{signal} are two polarizers.

$$\langle H_i | \Psi \rangle = \frac{1}{\sqrt{2}} (\langle H | H \rangle_i | V \rangle_s - \langle H | V \rangle_i | H \rangle_s) = \frac{1}{\sqrt{2}} | V \rangle_s \quad [2.3]$$

$$\langle V_i | \Psi \rangle = \frac{1}{\sqrt{2}} (\langle V | H \rangle_i | V \rangle_s - \langle V | V \rangle_i | H \rangle_s) = -\frac{1}{\sqrt{2}} | H \rangle_s \quad [2.4]$$

These measurements do not show nonlocality though, since type-II spontaneous parametric down-conversion in a classical regime will always generate pairs where for one photon of the pair being $|H\rangle$ polarized (or $|V\rangle$ polarized) the other photon will always be of the orthogonal polarization, so $|V\rangle$ polarized (or $|H\rangle$ polarized). Therefore, if an idler photon is detected in the horizontal polarization state $|H\rangle$, automatically that means that the signal photon will be in the vertical polarization state $|V\rangle$. But that also means that idler photons in the vertical polarization states are completely absorbed by the P_{idler} polarizer, and subsequently, are never detected.

There exists a polarization state that will highlight nonlocality and by doing so demonstrate properties unique to the quantum regime and unachievable in the classical regime. The cross polarization states $|+45\rangle$ and $|-45\rangle$ are described by an

equal amount of both $|H\rangle$ and $|V\rangle$ (see equation 2.3). When a measurement is made on the idler photons in the $|-45\rangle$ polarization basis for type-II SPDC, we see from equation 2.6 that the signal photon's polarization state is now $|+45\rangle$.

$$|+45\rangle = \frac{1}{\sqrt{2}} (|H\rangle + |V\rangle) \quad ; \quad |-45\rangle = \frac{1}{\sqrt{2}} (|H\rangle - |V\rangle) \quad [2.5]$$

$$\langle -45_i | \Psi \rangle = \frac{1}{\sqrt{2}} \left(\frac{1}{\sqrt{2}} (|V\rangle_s - |H\rangle_s) \right) = \frac{1}{\sqrt{2}} |+45\rangle_s \quad [2.6]$$

In order to validate the correlation in polarization, a polarizer is placed in the signal photon's optical path. Now each photon of each pair is going through the polarizers. As we have seen from equations 2.3 and 2.4, a measurement on the idler photon in the horizontal polarization state will result in defining a vertical polarization state for the signal photon and similarly a measurement of the idler photon in the vertical polarization state leads the signal photon to be in the horizontal polarization state. Ultimately, setting $P_{\text{idler}}: |H\rangle$ and $P_{\text{signal}}: |H\rangle$ or $P_{\text{idler}}: |V\rangle$ and $P_{\text{signal}}: |V\rangle$ will result in a probability of counting pairs of photons equal to zero, as shown by equations 2.7a and 2.7b respectively. Suitably, we will call this measurement, the 'null' measurement when referring to it.

$$|\langle H_s | \langle H_i | \Psi \rangle|^2 = \left| \frac{1}{\sqrt{2}} \langle H_s | V \rangle_s \right|^2 = 0 \quad [2.7a]$$

$$|\langle V_s | \langle V_i | \Psi \rangle|^2 = \left| -\frac{1}{\sqrt{2}} \langle V_s | H \rangle_s \right|^2 = 0 \quad [2.7b]$$

Although here, one could make an argument that such a measurement could be run classically. The optical setup can be imagined whereby pairs of photons are generated and the polarization of both photons of the pairs, let's call them idler_c and signal_c for the classical analog of a quantum idler photon and the quantum signal photon, are randomly set by a liquid crystal variable retarder to be either horizontally polarized or vertically polarized. In order to create the same orthogonal difference in polarization between idler_c and signal_c , a half-wave plate with its fast axis 45 degrees to the horizontal plane will orthogonally rotate the horizontally and vertically polarized signal_c photons to a vertical or

horizontal polarization correspondingly. In that situation, the measurement described by equations 2.7a and 2.7b in this classical analog will yield a detection of 0 photon pairs as well. On the other hand, with the classical photon polarizations limited to horizontal and vertical, the cross polarization measurement described in equation 2.6 will never yield a detection of 0 for any rotation of the signal polarizer. This is due to the fact that a measurement of horizontally or vertically polarized photons with +45 or -45 degrees will always transmit half of the total intensity of the classical state. On the other hand, in the quantum regime, with the same wavefunction, probability of detection will be null.

In the cross polarization measurement scheme described in equation 2.6, P_{idler} was set to transmit $|+45\rangle$. Therefore, the null measurement requires the P_{signal} polarizer to be set to transmit $|-45\rangle$. In that event, we observe from equation 2.9 that indeed, in coherence with the null measurement in the $|H\rangle$ and $|V\rangle$ polarization basis, the cross polarization also results in a probability of a biphoton joint-detection of 0.

$$\langle -45_s | +45_s \rangle = \begin{pmatrix} \cos(45^\circ) & -\sin(45^\circ) \end{pmatrix} \begin{pmatrix} \cos(45^\circ) \\ \sin(45^\circ) \end{pmatrix} \quad [2.8]$$

$$|\langle -45_s | \langle -45_i | \Psi \rangle|^2 = \frac{1}{\sqrt{2}} (\cos^2(45^\circ) - \sin^2(45^\circ)) = 0 \quad [2.9]$$

It is indeed possible to produce such a result with the classical source described previously but only by replacing the horizontal and vertical polarization states with ± 45 degree polarization states. But by doing that, now the null measurement is no longer possible for $|H\rangle$ and $|V\rangle$ states. In other words, polarization entanglement is unique to the quantum regime due to its ability to satisfy both the horizontal-vertical null measurement of 0 and the cross polarization null measurement of 0, an effect that classical sources may only display by locally modifying the polarization states.

The difference underlined from the previously mentioned null measurements is directly related to the CHSH inequality and Bell's inequality [21]. Both

inequalities are used to quantify the level of nonlocality of optical sources. In the situation in which a source does not satisfy a particular set of parameters, the source is defined as classical. Therefore, they validate if a source operates in the quantum regime or not.

For our entangled source, we measured the ‘Bell parameter’ which follows the Bell inequality. These sets of measurements have been widely used in the quantum optical community to authenticate degrees of nonlocality and more recently to define the new record high for the Bell parameter value [22, 23].

Previously, the ‘null’ measurements were described as the main characteristic for revealing the unique features of polarization quantum entanglement. Bell inequalities makes use of the same working principle by calculating a parameter, namely the visibility, that defines the contrast between maximum and minimum coincidences as a quality factor of the quantum state. The visibility’s general mathematical expression is formulated in equation 2.10a, where the minimum coincidence counts are obtained by means of conducting the ‘null’ measurement. The configuration required to measure the maximum coincidence counts is different from the ‘null’ measurement only in that the polarizer P_{signal} is no longer set to transmit the same state as P_{idler} , but instead the orthogonal polarization state. Two visibilities need to be calculated and measured. The first one is in the horizontal and vertical polarization basis denoted $V_{H/V}$ in equation 2.10b, and the second visibility is in the cross polarization basis described in equation 2.10c as $V_{-45/+45}$. For the two visibilities, the ratio is given in terms of the transmission polarization state of the idler polarizer, denoted P_i , and the signal polarizer P_s . In other words, $P_i|H\rangle P_s|V\rangle$ portrays a configuration where the idler polarizer is set to transmit the horizontal polarization and the signal polarizer is set to transmit the vertical polarization.

$$\text{Visibility} = \frac{\text{max coinc. counts} - \text{min coinc. counts}}{\text{max coinc. counts} + \text{min coinc. counts}} \quad [2.10a]$$

$$V_{H/V} = \text{Visibility } |H/V\rangle = \frac{P_i|H\rangle P_s|V\rangle - P_i|H\rangle P_s|H\rangle}{P_i|H\rangle P_s|V\rangle + P_i|H\rangle P_s|H\rangle} \quad [2.10b]$$

$$V_{-45/+45} = \text{Visibility } |-45/+45\rangle = \frac{\langle \text{Pi}|-45\rangle\langle \text{Ps}|+45\rangle - \langle \text{Pi}|-45\rangle\langle \text{Ps}|-45\rangle}{\langle \text{Pi}|-45\rangle\langle \text{Ps}|+45\rangle + \langle \text{Pi}|-45\rangle\langle \text{Ps}|-45\rangle} \quad [2.10c]$$

$$S = \sqrt{2} (V_{H/V} + V_{-45/+45}) \quad [2.11]$$

When these visibilities are calculated, they are introduced in the S parameter (also called the Bell parameter) devised in equation 2.11. A polarization quantum entanglement source is only validated when the S parameter is strictly greater than 2. The source I built for this experiment successfully resulted in S-parameter of 2.66 ± 0.01 , which is greater than 2, which means that the photon pairs display nonlocal properties.

Figure 2.3 - Visibility curves for $V_{H/V}$ (dashed line with red circular markers) and $V_{-45/+45}$ (solid curve with purple circular markers).

The visibility curves displayed in figure 2.3 were measured by setting the idler polarizer to $|V\rangle$ and $|-45\rangle$ while the signal polarizer was rotated within a range of $\theta = \sim 190$ degrees and coincidences were measured for an increment of $\theta = \sim 5$ degrees. The dashed curve represents the fitted visibility $V_{H/V}$ of the experimental data (red circular markers). And similarly, the solid curve depicts the fitted visibility $V_{-45/+45}$ of the experimental data (purple circular markers). I will now proceed onto describing the optical setup and alignment procedure for building the polarization entangled source.

2.2.2.2 – Optical Setup/Alignment:

The polarization entangled photon pairs are generated by the virtue of type-II spontaneous parametric down-conversion (SPDC) with 2mm thick beta-barium borate (BBO) crystal with phase matching angles of $\theta = 41.9^\circ$ and $\phi = 30^\circ$. This crystal operates for a pump laser (Omicron, LUXx 405-300) wavelength of 405nm and generates down-converted photon pairs of 810nm in wavelength.

In this section I will only mention the most important steps in the alignment procedure as to not overly develop on something which has already been established in the field.

In accordance with the introduction on type-II SPDC in previous sections, light cones are generated in the birefringent crystal. These cones need to be intersected at two points which is where the superposition of states occurs. An idler photon found in one intersection, has its respective signal photon of the pair in the other intersection. In order to improve our knowledge of the cones, a ‘2D imaging scanner’ (2DIS) was built from two motorized single axis linear stages and an L-bracket. Depicted in figure 2.4, our homemade device scans a two dimensional plane, during which a multimode fiber tip couples to the incident single photons from the SPDC cones and sends them to a single photon counting module (SPCM). An electrical pulse travels through a BNC cable to the coincidence counting module, at which point the labview program in the computer console registers the counts and assigns them for a specific x,y coordinate of the 2D array.

Figure 2.4 - Diagram of the 2D imaging scanner. A labview program sends commands to the linear stage motors. At each position of the linear stages, single and/or coincidence counts are recorded onto the labview program.

This program runs in a loop for specified x and y coordinates. At the end of the scan, an image of the SPDC cones is obtained. In that way, we could image the cones to verify the phase matching condition and that the cones are intersecting. A similar technique is adopted by other experimentalists by way of using EMCCDs and CMOS cameras.

Figure 2.5 - Imaging the generation of SPDC cones for different tilts of the BBO relative to the incident pump beam with the 2DIS.

Shown above are examples of scans and of the importance of having the proper vertical tilt. The cone configuration needed for polarization entangled photon pairs is depicted in Figure 2.5. As we change the tilt, the cones get smaller and move away from each other. In this situation, there no longer are two intersections, at best just one intersection.

With the proper configuration of cones, an optical rail was screwed into the optical table perpendicular to the direction of the 405nm pump beam. The role of this rail is to keep the setup completely symmetrical.

At this stage, right angle mirrors, denoted RAMs, were placed on the optical rail for each intersection of the SPDC cones. First, the left and right intersections, denoted path I and path II, were imaged from their reflection off of the RAMs (see figure 2.6(c) & 2.6(d)). In order to validate that the intersections are aligned with the optical rail, a pinhole (PH) was placed in each path on the rail with a calibrated height, in consequence the intersections passing through the pinholes were imaged and are depicted in Figure 2.6(a) for path I and figure 2.6(e) for path II.

Figure 2.6 - Alignment of the right angle mirrors (RAMs). (c) and (d) are the imaged intersections without the pinholes for paths I and II respectively. (b) and (e) are the imaged intersections with the pinholes for paths I and II respectively.

Furthermore, the 2DIS was moved all the way down the rail, to where the couplers for the final setup will be with another pinhole in front of it. This measurement is to ensure that the intersections are aligned properly over the

distance where other optics will be needed to be placed. The resulting scans showed that the intersections were there but that the photons diverged to such an extent that the imaging appears with very low contrast. In other words, the intersections were now too large to be detected by our couplers, thus the intersections needed to be collimated. This was done by placing lenses in optical paths I and II between the two pinholes, illustrated in figure 2.7(e).

Figure 2.7 - (a)-(d) 2DIS scans of the intersections for different positions of the collimating lens (CL) placed in between the two pinholes (PH) in both paths in the optical setup shown in (e).

The collimation is not only important for imaging but also in that if photons that do not belong at the intersection and thus belong only to one cone, find themselves at the intersection, these mixed state photons will lower the purity of quantum state. In this situation, their presence will be made obvious by increasing the minimum of the visibility for the cross polarization quantum states.

In order to find the optimal position for the lenses to collimate the beam properly, scans for all different positions were conducted, depicted in figure 2.7(a)-(d). Figure 2.7(a) shows the first position. In this collimation scan the inner and outer rims of the cones barely appear, which shows a poor collimation. On the other hand, we notice the more the collimating lenses are moving in the direction of the second PH, the better the collimation. The quality of collimation is observed here through the fact that more of both the inner and outer parts of the rims of the cones are imaged (see figures 2.7(b)-(d)).

Figure 2.8 - Final optical setup with the half-wave plates (HWP) and compensating BBO crystals (CC).

Once the collimating lenses are optimally positioned, two very important components need to be placed in each path. When the photon pairs are generated, one photon of the pair will be generated through the extraordinary axis of the BBO crystal, while the other photon will be generated through the ordinary axis. The differences between these two axes include the fact they are defined by two different refractive indices of the birefringent nonlinear medium. Hence, that means that one photon will be transmitted out of the crystal slower than the other one. Thus, the photons are distinguishable from each other in time and position. This generation-induced delay is called ‘temporal walkoff’ and ‘spatial walkoff’. Since ordinary and extraordinary axes are polarization dependent, the walkoffs can be compensated by rotating each photon to the perpendicular polarization and transmitting them through the same thickness of BBO crystal they transmitted through initially, which is on average, half the thickness of the crystal. This is done by placing a half-wave plate and a compensating BBO crystal (CC) of the same phase matching angle but of half the thickness (thickness = 1mm) as depicted in figure 2.8. This also means that the CCs need to fit exactly the same tilt and rotation for phase matching as the initial 2mm thick BBO.

Figure 2.9 - Compensation crystal profiles for a rotation change and a tilting change of the configuration relative to the input pump beam.

In order to produce that condition, the CCs were tilted and rotated in different orientations in order to understand how to reproduce exactly the same phase matching angles. This was done with the redirected 405nm pump laser that was reflected on a mirror placed in front of the 2mm BBO. The most important parameters are depicted in figure 2.9, which are the angles of rotation and the vertical tilt. We see from the figure that the rotation of the crystal mount will rotate the cones towards the left or the right and the vertical tilt will either create one intersection of the cones or two. The tilts were calibrated by conducting back reflection off of the BBO crystals and retrieved the difference between the back reflected beam and the level of the incident beam.

After optimizing both CCs, their scans were compared and indeed suggest an equivalence in the spatial configuration of the cones, as depicted in figure 2.10.

Figure 2.10 - On the left, the scan for the 2mm thick BBO, on the right, one of the scan for the 1mm thick BBOs.

With all the necessary optics aligned to obtain polarization entangled photons, all that needed to be done was to align each coupler with the same part of each intersection. The part of the intersection that needs to be coupled into is characterized by 1) having equal amounts of horizontal and vertical polarized photons and 2) to be positioned where there exists the highest counts for both single photons and coincidences. With respect to the latter, one of couplers was kept fixed at a point in the intersection, while the other performed a scan in single counts. Both coincidences and single photon counts are retrieved after which they are compared both in the x-coordinate and y-coordinate. This comparison is shown in figure 2.11.

Figure 2.11 - The single photon scan in the bottom left frame is compared with the coincidence counts in the bottom right frame and top left frame for the y and x coordinates respectively.

In the comparison figure, the highest counts are where the pixels are of a white color, as opposed to the blue color, representing lower counts. Two drawn frames serve as a post-processing aligner to verify that the x and y coordinates for single and coincidence counts are aligned. If they are not, the position of the fixed coupler is changed and the intersection is scanned again. This figure shows the last scan, which illustrates that the highest single counts are indeed aligned with the highest coincidence counts in both the x and the y direction. As a result, as per the visibility curves in figure 2.3, this alignment successfully provided polarization entangled photon pairs with type-II SPDC.

2.3 - Fabrication and Characterization Processes

Figure 2.12 – Ordered steps for producing the metamaterials

2.3.1 - Software Simulations with COMSOL

Optical metamaterials are unique in their abilities to exhibit specific properties. These properties are dependent on the material’s characteristics, which are, to name a few, the refractive index (n), the permittivity (ϵ), the permeability (μ). In my case, the metamaterials required a specific absorption constant, and for both transmission and reflection constants to be equal. Hence, before fabricating, the parameters of the metamaterials required to be simulated as shown to the left in figure 2.12. The simulations were produced on a finite element method (FEM) software called COMSOL. Some of the many functionalities this software can reproduce are unique to simulating the optical properties of varieties of

nanostructured designs at different wavelengths by using maxwell's equations. The computed results will then confirm the nanostructure's design in yielding particular optical effects.

2.3.2 - The Fabrication Hardware

Once the targeted values for the reflection, transmission and absorption coefficients have been produced by compiling COMSOL simulations, the metamaterials can be fabricated as shown in figure 2.12 in the center.

The metamaterials were made of a thin gold layer, thus the first step was to evaporate it onto the silicon nitride membrane. Such a task is carried out by using a thermal evaporator, which is an instrument that uses electrical current inside of a vacuum chamber to apply heat to a metallic slab called a 'boat' that contains a 1-2mm gold 'donut'. For a specific temperature, the 'donut' evaporates uniformly in an upward direction. As a result, the evaporated gold particles settle on the 'ceiling' of the chamber where the substrate has been fixed. This instrument varies in the quality of deposition based on how clean the substrate is, the deposition rate, the level of the vacuum and more [24].

Then in the interest of producing a gold freestanding layer for my experiments, our collaborator (Dr. Joao Valente) made clever use of a particular feature of a commercialized 5mmx5mm Silicon Nitride membrane. The membrane was the same 200µm thickness throughout except for a centered square-shaped area for which the thickness of the membrane was only 50nm. As a result, after having thermally evaporated the 50nm gold layer, the silicon nitride was then removed from the bottom (opposite side of the membrane from where the gold was deposited) by using a Reactive ion etching (RIE) technique. RIE uses both physical and chemical processes to remove material by introducing gas (in our

case fluoroform (CHF_3) and argon (Ar) gases) to react with the membrane in the vacuum chamber. With the optimized recipe, the result was a 50nm layer of gold in the centered area of the membrane. Upon the reception of the freestanding from our collaborator, the nanostructure could then be fabricated. In order to create features on the nanometer scale, a focused ion beam (FIB) was used. This instrument removes material with high precision by virtue of discharging ions repeatedly to the surface. (The amount of ions per surface area per unit time defines the quality of the nanostructure.)

2.3.3 - The Characterization Hardware

Two types of characterization techniques were required in order to define the quality of the nanostructured arrays fabricated. The first technique images the nanostructures and the second technique retrieves the optical properties of the fabricated nanostructures.

The first technique consists in imaging the individual arrays by using a scanning electron microscope (SEM). This high definition imaging device scans electrons that collide and interact with atoms on the surface of the nanostructures. As a by-product of generating different signals for different atoms, an image can be processed.

The second technique retrieves the spectrum in wavelength in both reflection and transmission by using a microspectrophotometer as shown in figure 2.12 on the right. This instrument produces different wavelengths for which as a result of interacting with the aligned nanostructure arrays, the reflection and transmission coefficients are detected. These results can be then compared with the simulation results.

Chapter 3

Quantum Coherent Perfect Absorption

3.1 - Introduction

Coherent absorbers were first theoretically formulated by Chong *et al.* [25] whereby a physical phenomenon enables materials that generally do not absorb radiation efficiently, to highly absorb. They reported that light can interfere in a material and, with a specific type of material-dependent dissipation, incident radiation may be trapped.

They expanded their theory by describing a situation in which two beams are incident in two single mode fibers joined together by a two channel resonator. Light coming from both sides endures reflection, transmission and absorption. Reflection can destructively interfere with transmission on one side and similarly on the other, which can render radiation to be trapped in the form of an interference pattern within the material and lost entirely to dissipation.

Figure 3.1 - Illustration of two single mode fibers joined by a two channel resonator where two beams, Beams A and B, are counter propagating and for which the reflection of one beam interferes with the transmission of the other beam, and vice versa.

Chong *et al.* also theoretically define how coherent absorption can be optimized to obtain ‘perfect absorption’. A crucial condition to satisfy is for reflection and transmission intensities to be equal. More than that though their relative phase must be producing constructive interference, which means that the relative phase must be either 0 or π . Hence, by changing the relative phase, the absorption levels may be modulated, and by association, control of the material’s absorption is possible.

In other words, as illustrated in figure 3.1, this system can be described as an analog of an interferometer for which the refractive index of the fiber is 1 (for air). The dissipation is crucial to producing coherent absorption, which is generated by the previously mentioned two channel resonator. Hence, we can simplify their illustration with an interferometer made of bulk optics that houses a ‘two channel resonator’. The absorption may be modulated by changing the relative phase in free-space, which can be accomplished by using several known techniques including: displacing a mirror in one of the optical paths, or equivalently, adding a delay stage, or alternatively changing the position of the material. All of these techniques create differences in lengths of the optical paths of the interferometer, which is comparable to creating a relative difference in

phase. This fact will be apparent in the section of this chapter which covers the theory on the quantum version of the coherent absorber with single photons.

This first publication created an important link between the interference phenomenon in the classical regime and absorption of radiation. The two beam configuration was then experimentally shown [26] with a Mach-Zehnder interferometer. The material is a silicon wafer of approximately 110 micrometers in thickness. By using a single axis delay stage in one of the optical paths of the interferometer, they show that coherent perfect absorption is achievable but that their experimental apparatus could be improved due to the fact that their CPA is operating near the band-edge of the material. A solution that they suggest as an alternative is to fabricate devices for which a parameter tunes the absorption coefficient for any wavelength in order to set the operating wavelength by design.

Wan *et al.*, through this paper, created an interesting opportunity for scientists working in the field of plasmonics and metamaterials. They suggested to find a technique through which one could fabricate a material whose absorption level could be tuned for different wavelengths.

The idea of CPA was first adapted to the plasmonics field of research with an idea to reproduce it with subwavelength thin plasmonic metamaterials [27]. Zhang *et al.* showed that complete absorption of light can occur by placing a plasmonic metamaterial that absorbs 50% of a traveling wave of the working wavelength. By placing the metamaterial in the path of a standing wave in an interferometer, modulation of absorption from 0 to 100% was achievable. This was realized by moving the metamaterial from the standing wave's node to the antinode in the scale of a few nanometers with a piezometric stage. At the standing wave's node, the magnitude of the electric field is null, hence the interaction between the nanostructures and the light is minimal, providing the 'coherent perfect transmission' regime. On the other hand, at the standing wave's antinode, the magnitude of the electromagnetic field is unitary, the interaction between the nanostructures and the light is at its highest, providing the 'coherent perfect absorption' regime.

Figure 3.2 - Coherent control with standing waves. On the left, coherent perfect transmission, on the right, coherent perfect absorption.

Courtesy of Zhang *et al.*.

This absorption of light into plasmons can be produced by creating nanostructures that resonate at the working wavelength. Absorption must be 50% and according to the following equation:

$$\text{absorption} + \text{transmission} + \text{reflection} = 1 \quad [3.1]$$

the sum of transmission and reflection will be 50% as well. As mentioned previously from the theoretical description of coherent perfect absorption by Chong *et al.*, it is rather clear that for an absorption of 50% and with the requirement to have reflection and transmission be equal, reflection must be 25% and transmission must be 25% as well. For the purpose of quantifying quality of fringes, the term visibility will be used throughout this manuscript, calculated by dividing the difference between the maximum detected intensity at the interferometer's outputs and the minimum intensity at the interferometer's outputs by the sum of the maximum and minimum detected intensities:

$$\text{Visibility} = \frac{\max \text{ det. } I - \min \text{ det. } I}{\max \text{ det. } I + \min \text{ det. } I} \quad [3.2]$$

In order to fabricate this metamaterial, a 50nm thick layer of gold was evaporated on a silicon nitride membrane. A focused ion beam (FIB) was used to fabricate the nanostructured arrays of asymmetric split rings. The design of the nanostructures is crucial in order to resonate at the working wavelength and absorb light by the right quantity. The parameters of each 'asymmetric split ring' structure in the square array can be simulated through the use of a 'finite element method' (FEM) software. The one most frequently used and used for all

experiments in this manuscript is COMSOL, which uses Maxwell's equations to simulate electromagnetic fields interacting with materials (introduced in chapter 2).

In the paper, Zhang *et. al.* highlight their experimental results, as depicted in figure 3.3, that demonstrate the noticeable difference between placing an unstructured gold layer (purple curve) and a nanostructured gold layer (red curve) of the same thickness in the standing wave of their interferometer. By moving the piezometric stage, the unstructured layer of gold shows very low modulation, roughly 76% at its minimum (or maximum absorption) to 96% at its maximum (or minimum absorption) of total output intensity. In contrast, replacing the unstructured layer of gold with an 'asymmetric split ring' nanostructured layer of gold, yields a superior modulation ranging from a maximum total output intensity of 94% and a minimum total output intensity of 14%. In other words, to refer to equation 3.2 that defined the mathematical representation of visibility, the visibility of fringes differs from $\sim 11\%$ for unstructured gold to $\sim 74\%$ for nanostructured gold.

Figure 3.3 - Absorption modulation – Metamaterial (red curve) vs. unstructured gold (blue curve).

Courtesy of Zhang *et. al.*

Using a metamaterial effectively shows high modulation comparable to the experimental work that matched the theory by Yidong *et al.* In the above figure the modulation from the coherent absorption regime is achievable for the 2π

phase ϕ . Such a low total output intensity is attainable when the absorber is at the antinode of the standing wave. By changing the relative phase and destructively interfering counter-propagating coherent beams, total output intensity is increased.

The theory of coherent absorbers highlighted the importance of interference effects in the classical regime. Interference though, is not only qualified as a classical effect, it also has been shown to be specific to the quantum regime with the wave-particle duality, of which the most well-known example for quantum states of light is ‘Young’s two-slit experiment’ with single photons. Hence, if quantum states of light can both dissipate and interfere in a material, coherent absorption should be observable in the quantum regime.

The first adaptation of the two beam coherent perfect absorption effect in the quantum regime was in the form of a theory. S. Huang and G.S. Agarwal [28] describe coherent perfect absorption of a single photon.

It has been well established that a single photon can interfere with itself [29, 1]. In this type of situation, we may say that the single photon is path entangled. Path entanglement is a property in which a photon is in superposition of two states which are specific to the path it takes to a detector. If the photon has equal probability of taking two paths a and b, it will propagate through both paths in the form of a wave. If the relative phase of the paths can be modulated, this system is described by the following probability amplitude:

$$|\Psi\rangle = \frac{1}{\sqrt{2}} (|1\rangle_a |0\rangle_b + e^{i\phi} |0\rangle_a |1\rangle_b) \quad [3.3]$$

Where $|1\rangle_a$ denotes that the photon goes through optical path a and hence $|0\rangle_b$ denotes that the photon does not go through path b. The second part of the wavefunction within the parentheses is a description of the second possibility of path taken by the photon, which is that the single photon does not take path a but instead path b to the detector. $e^{i\phi}$ denotes the relative phase:

$$e^{i\phi} = \cos \phi + i \sin \phi \quad [3.4]$$

The probability of detection can be found by computing the modulus square of the probability amplitude:

$$||\Psi\rangle|^2 = \left| \frac{1}{\sqrt{2}} (|1\rangle_a |0\rangle_b + e^{i\phi} |0\rangle_a |1\rangle_b) \right|^2 = 1/2 \cos^2 \frac{\phi}{2} \quad [3.5]$$

By computing the modulus square of this probability amplitude for different relative phases ϕ from 0 to π , one can compute the interference fringes from the intensity detected.

In their theoretical work, S. Huang and G. S. Agarwal describe an interferometer. The superposition is generated from a 50:50 beamsplitter, thereby creating two optical paths $a_{in}(\omega)$ and $b_{in}(\omega)$, where ω denotes the frequency of the incident single photons.

Figure 3.4 - Representation of the optical scheme used in Huang and Agarwal's work on theory of CPA with path entangled single photons. The input single photons are incident on a beamsplitter BS. Two optical paths $a_{in}(\omega)$ and $b_{in}(\omega)$ are generated of lengths l_1 and l_2 respectively. The single photon reflects, transmits or is absorbed at a medium. The outputs are collected, denoted $a_{out}(\omega)$ and $b_{out}(\omega)$.

At the interface of the coherent absorber, denoted by a medium with a refractive index of $n_1(\omega)$, the single photon will interfere with itself. Through the use of this scheme, by changing the difference between the length of path $a_{in}(\omega)$ and path $b_{in}(\omega)$ denoted l_1 and l_2 respectively, the output intensities can be modulated as a function of absorption of the medium.

The main difference with the original theory for coherent absorbers lies within the interpretation of interference of a single photon. In the classical theory, classical interference is produced with a summation of waves. Oppositely, quantum interference is probability based. Two photons do not sum themselves together since there is only one photon at a time at the material.

Therefore, if the medium can perfectly absorb, a single photon can be absorbed with 100% probability.

3.2 - Coherent Perfect Absorption of a Single Photon

The first experiment was conducted in collaboration with a laboratory in Heriot-Watt University. It consisted in fully absorbing a single photon that displayed wave-particle duality. The absorption was produced by a metamaterial in an optical interferometer apparatus.

In this work, the quantum theory of coherent perfect absorption was demonstrated for the first time. Similarly to the classical experiment, a plasmonic metamaterial which is best described by an array of asymmetric split ring nanostructures was used to perfectly absorb light. By virtue of changing relative phase in an interferometer, the results show that intensity at the output can be modulated based on the interaction between the path-entangled interfering single photon and the nanostructured plasmonic coherent absorber.

Differently from the classical experiment [27], interference of a single photon is not a result of the summation of propagating coherent waves. Following the wave-particle duality, a single photon interferes with itself by way of being in superposition of optical paths in the form of a wave. Since 'perfect' coherent absorption is characterized by a level of absorption which nearly reaches 100%,

coherent perfect absorption with single photons demonstrates the ability to coherently absorb a single photon with close to 100% probability.

In order to demonstrate coherent perfect absorption in the quantum regime, an optical Sagnac-like interferometer, and a single photon source were built. In addition, a plasmonic coherent absorber was engineered to produce a 50% absorption.

3.2.1 - The Plasmonic Metamaterial

As expressed both by the classical theory of CPA [25] and, more importantly, the quantum theory of CPA [28], particular attention is drawn to the reflection and transmission coefficients of the absorber. In order to produce a ‘coherent perfect absorption’ regime, the absorber needs to have a reflection coefficient equal to the transmission coefficient on both sides. Therefore a plasmonic ‘freestanding’ metamaterial made of an array of asymmetric split-ring nanostructures was fabricated by our collaborator Dr. Joao Valente.

A 50nm thick layer of gold was thermally evaporated on a 5.0mm x 5.0mm Silicon Nitride membrane. The thickness of the membrane is uniform throughout except for a centered squared-shaped area of 250 μ m x 250 μ m for which the thickness is of 50nm. In order to provide an equal reflection coefficient from both sides, the layer of gold was rendered ‘freestanding’, a term that describes having a single layer of gold surrounded by air. This is produced by dry-etching the 50nm thickness of silicon nitride in the center of the membrane (as mentioned in chapter 2), thus, the 50nm freestanding layer is held in place by virtue of surface contacts with the Silicon Nitride frame.

With a high quality freestanding layer, the film was then nanostructured by using a focused ion beam (FIB). Several nanostructured arrays were fabricated and characterized in reflection, transmission and absorption. For very specific parameters of each nanostructure of a metamaterial array, the desired reflection,

transmission and absorption levels for the working wavelength of the single photons of 810nm was fabricated, as depicted in figure 3.5b. These parameters optimized for specific reflection, transmission and absorption constants were obtained by simulating for particular effective permeabilities and effective permittivities by using a COMSOL software. By controlling the unit cell size, the periodicity, and slit widths and lengths, levels of absorption due to plasmonic resonances can be tuned. The spectra shown below illustrates the transmission and reflection profiles for both unstructured gold film (dashed curves) and the metamaterial (solid curves). We observe that the resonance structures bring the reflection down to $\sim 25\%$ and similarly the transmission is increased to $\sim 25\%$.

Figure 3.5 - (a) SEM image of the plasmonic nanostructured array for which the optical properties are measured in (b).

Our absorber now meets the criterion for reflection and transmission with 50% absorption. It is then placed in the interferometer and aligned with the single photon source.

3.2.2 - The Optical Apparatus

In order to demonstrate coherent perfect absorption in the quantum regime, an optical setup that supported the interference of single photons was built. Though, first and foremost, the source needed to be validated as a single photon source,

which was produced by conducting the following auto-correlation measurement shown below in figure 3.6 and for which this particular type of measurement was introduced in Chapter 2.

Figure 3.6 - Results from the $g^{(2)}(0)$ measurement produced from the SPDC source.

As illustrated in figure 3.7, the idler photon of each pair is sent directly to a single photon counting module (SPCM) used to register the counts of pairs (green rectangle) by heralding the arrival of the signal photon from the outputs of the interferometer. Meanwhile, the path entangled wavefunction of the signal photon of the pair is interfering with itself in the Sagnac interferometer (yellow square).

Figure 3.7 - Illustration of the optical setup used for demonstrating coherent perfect absorption of a single photon.

In fact, path entanglement is generated by the beamsplitter BS in the creation of two optical paths α and β to the plasmonic metamaterial. We may formulate the path entangled wavefunction as the following:

$$|\Psi\rangle = \frac{1}{\sqrt{2}} (|1\rangle_{\alpha}|0\rangle_{\beta} - e^{i\phi} |0\rangle_{\alpha}|1\rangle_{\beta}) \quad [3.6]$$

The wavefunction outlines the superposition of the photon taking paths α and β with a relative phase variable denoted $e^{i\phi}$ normalized with a factor of $\frac{1}{\sqrt{2}}$.

The single photon may be reflected, transmitted or absorbed by the previously mentioned coefficients, which we have determined as 25%, 25% and 50% respectively for the working wavelength of the single photons of 810nm. These are collected simultaneously at both outputs γ and δ by using lenses to optimally couple light into optical fibers. The idler photons are detected by the single photon counting modules and registered at the coincidence counting module with the signal photons.

3.2.3 - The Results

The phenomenon of coherent perfect absorption is highly dependent on relative phase. Hence, the results are produced by changing relative phase, which is the difference in phase between both optical paths of the interferometer, in this experiment denoted α and β . A relative phase $\phi = 0$ will generate constructive interference, while a destructive interference will occur for a relative phase $\phi = \pi$. As mentioned previously, in this experiment relative phase is modulated by virtue of tuning the difference in path lengths with a nanometer-precise piezoelectric stage. The method unintentionally follows Huang *et al.*'s mathematical notation from their quantum theoretical formulation of CPA. They describe relative phase with $e^{ik(\ell_{\alpha} - \ell_{\beta})}$, whereby k is the wavevector $k = 2\pi/\lambda$, for λ is the wavelength of single photons, and ℓ_{α} , ℓ_{β} denote the lengths of optical paths α and β .

Figure 3.8 - Heralded photon counts (a) for output γ normalized to input α , (b) for output δ normalized to input β , (c) averaged normalized counts of γ and δ and (d) for a 30-layer chemical vapor deposition-grown graphene film as a function of the sample position.

The sub-figures shown above in figure 3.8 represent normalized coincidence counts at each output. Figure 3.8 (a) displays the coincidence counts at output γ normalized to α and (b) the coincidence counts at output δ normalized to β . The solid line fits the experimental normalized heralded photon counts, represented by filled circular markers. The hollow circular markers represent the heralded photon counts when optical path β of the interferometer is blocked. These points will therefore only show reflection of α in figure 3.8 (a) and transmission α in figure 3.8 (b), which is yielded in the figure and confirmed by characterizing the metamaterial at 25%. In other words, these points show that reflection is equal to transmission inside of the interferometer. On the other hand figure 3.8 (c) shows the sum of both outputs of the interferometer whereby a modulation of relative phase displays coherent perfect transmission and coherent perfect absorption. In parallel, the same measurement was produced with a 30-layer graphene film in figure 3.8 (d), thus illustrating that the absorption characteristics required for CPA can be emulated with unstructured films of specific plasmonic materials.

Thus, in this collaboration with Heriot-Watt University, the first experimental ‘quantum’ coherent perfect absorption of single photons was demonstrated. This experiment motivates a new direction in combining quantum optics with nanostructured metamaterials. Further, it defines a parallel between experimental quantum and classical interferences that paves the way for understanding if highly pure quantum states may permit for a nonlocal control of coherent perfect absorption.

3.3 - Coherent Perfect Absorption with Entangled Photon Pairs

As was previously demonstrated in this chapter, coherent perfect absorption was achieved with a plasmonic asymmetric split-ring array metamaterial with single photons. By changing the relative phase in the Sagnac interferometer, the heralded photon counts define two regimes: ‘coherent perfect absorption’ and ‘coherent perfect transmission’. The metamaterial was fabricated on a freestanding gold film and had, on both sides, optical properties characterized to be reflection = transmission = 25%, and absorption = 50%. Therefore, the results demonstrated the ability to coherently absorb in the quantum regime.

The quantum regime, though, describes more than one quantum state of light. Indeed, this regime represents a variety of properties. For instance, the previously mentioned quantum regime is best described by interference of a path-entangled photon in which the wavefunction is path-dependent (see equation 3.6). In this third section of chapter 3, I am reporting the experiment that lies at the center of my thesis. In this experiment, I built a polarization entangled photon setup (which includes quantum optical alignment and engineering the detection scheme), aligned a Sagnac interferometer (with the guidance of Dr. Stefano Vezzoli), and nanostructured the freestanding plasmonic absorber. All these different parts of the experiment will be presented in what follows.

3.3.1 - The Concept

In the experiments that follow, we use the established knowledge from the previous work that a single photon can be coherently absorbed into a plasmon to investigate nonlocal quantum coherent perfect absorption. The novelty comes from the fact that, in this experiment an ‘observer’ will be able to dictate the existence or absence of coherent perfect absorption for all relative phases in the interferometer nonlocally. In order to produce such a scenario, a new quantum source needed to be built, which this time is not only generating heralded single photons but also polarization entangled photons (as explained in chapter 2). Furthermore, for the purpose of creating a regime in which CPA cannot occur, a quantum eraser interferometer was produced.

3.3.2 - The Quantum Eraser

In terms of classical optics, two coherent traveling waves can interfere by virtue of the summation of their fields that make up a standing wave. This has been well illustrated by Zhang *et al.* in figure 3.2. But in fact, if the polarization of one beam is horizontal (TM) and the other is vertical (TE), no interference will take place. This is because the electric and magnetic fields are not compatible for that purpose.

The interpretation is very different in quantum optics. Interference of a single photon only occurs for indistinguishable optical paths, which is defined as path entanglement. This means that if an observer can discover which path the photon took, then the photon obviously cannot be also detected in the other path, which means that it no longer interferes with itself [29, 1, 2]. As a result, the photon has been conditioned by the observer to take the form of a particle traveling through a single optical path. This scenario is easily translated through its quantum representation by using the path-entanglement wavefunction from equation 3.6 displayed below:

$$|\Psi\rangle = \frac{1}{\sqrt{2}} (|1\rangle_{\alpha}|0\rangle_{\beta} - e^{i\phi} |0\rangle_{\alpha}|1\rangle_{\beta}) \quad [3.7]$$

We can thus produce a projection on one of the paths, for instance the detection of one photon in optical path α . In this case, it becomes clear that no interference will occur:

$$\langle 1_{\alpha}|\Psi\rangle = \frac{1}{\sqrt{2}} |0\rangle_{\beta} \quad [3.8]$$

The observer has collapsed the wavefunction, and knows the ‘which-path information’ (WPI) also called the *welcher weg*. This wave-particle duality-specific behavior of the single photon has been particularly well documented both theoretically and experimentally with the quantum eraser [30, 31, 32].

Due to the fact that this optical scheme occupies a central role in our experiment described in this section, I will now formulate what a quantum eraser is in terms of an interferometer.

The interferometer depicted below in figure 3.9 is composed of a 50:50 beamsplitter that generates two optical paths. With equal probability, the photon is either transmitted through or reflected. One polarizer is placed in each optical path. The polarizer in optical path b only transmits horizontally polarized photons denoted $|H\rangle$, and absorbs vertically polarized photons. In contrast, the polarizer in optical path a only transmits vertically polarized photons denoted $|V\rangle$, and absorbs horizontally polarized photons. Each optical path is reflected by 90 degrees to the second 50:50 beamsplitter where the photon may either be reflected or transmitted. The single photons are then detected at a single output d in front of which a polarizer P_{out} measures the polarization state.

Figure 3.9 - Simple representation of a Mach-Zehnder quantum eraser.

Let's consider the situation in which the polarization of all incident single photons are $|H\rangle$ and the polarizer P_{out} transmits $|H\rangle$. In that configuration the observer knows that the single photons traveled through optical path b and was reflected on the output beamsplitter. Hence, the WPI is retrieved, thus no interference occurs. Similarly a detected $|V\rangle$ polarized single photon transmitted through P_{out} set to $|V\rangle$ will yield no interference since the WPI obviously points to the photon having taken path a.

Equivalently, if the single photons incident to the interferometer were generated randomly to be of either $|H\rangle$ polarized or $|V\rangle$ polarized, the selective transmission of P_{out} in either $|H\rangle$ or $|V\rangle$ would still provide the observer with the WPI. The lack of interference at the detector can be derived by projecting on its wavefunction defined as follows:

$$|\Psi\rangle_d = \frac{1}{2} i (|V\rangle - e^{i\phi}|H\rangle) \quad [3.9]$$

The detector denoted $|\Psi\rangle_d$ in the absence of polarizer P_{out} will detect both vertically polarized photons belonging to path a and horizontally polarized photons belonging to path b. The factor of $\frac{1}{2}$ represents the normalization of the two beamsplitters and the i is the added phase created by the mirrors reflecting by 90 degrees. Since here we are not particularly interested in quantifying the probability but more in the existence or absence of interference, I simplify the expression to:

$$|\Psi\rangle_d = (|V\rangle - e^{i\phi}|H\rangle) \quad [3.10]$$

When the observer places the polarizer P_{out} set to transmit the vertical polarization $|V\rangle$ or horizontal polarization $|H\rangle$ in front of detector d, we obtain the following expressions:

$$|\langle V|\Psi\rangle_d|^2 = 1 \quad [3.11]$$

$$|\langle H|\Psi\rangle_d|^2 = 1 \quad [3.12]$$

The probabilities of detection produced by taking the modulus square of the projected probability amplitudes yield a constant which means that no interference fringes occur as a function of relative phase (of course the probabilities are unitary because for simplicity the normalization constant was removed. Both the probabilities with the normalization constant give 0.25).

Hence, this derivation is coherent with the previous statements. More interestingly, the WPI may be erased with the measurement of a state with P_{out} that does not single out a particular polarization, but instead, reinstates indistinguishability. This particular state is the ± 45 degree polarization. I choose to use the +45 degree polarization, although -45 is an ‘eraser’ state as well. We notice that from the quantum description in equation 3.13, the $|+45\rangle$ state is composed of an equal contribution from the horizontal and the vertical polarizations. Thus, when the observer sets P_{out} to +45 degrees, detecting a photon will only convey that either that photon was horizontally polarized or vertically polarized with 50% probability. In that situation only interference occurs, validated here in equation 3.14.

$$|+45\rangle = \frac{1}{\sqrt{2}} (|H\rangle + |V\rangle) \quad [3.13]$$

$$|\langle +45|\Psi\rangle_d|^2 = \sin^2 \frac{\phi}{2} \quad [3.14]$$

Therefore, if the polarizer is set to +45 degrees, the variation of the relative phase ϕ will produce interference fringes, but measuring the horizontal or vertical polarization states will result in a constant probability as a function of ϕ . Consequently, the quantum eraser defines a method by which the photon's WPI can be made available, in which case no interference occurs. On the other hand, when the WPI is erased, interference of a single photon can take place.

As mentioned in the beginning of this section, proof of erasing WPI is recorded at the interferometer's output. Our experiment then presents an added level of complexity in producing a coherent perfect absorption regime. More specifically, a polarization biased metamaterial characterized with a higher transmission of $|V\rangle$ polarized photons or of $|H\rangle$ polarized photons, would provide the WPI, and thus no CPA would occur. Hence, attention was directed towards fabricating a polarization-independent metamaterial for the purpose of producing coherent perfect absorption with polarization entangled photons.

3.3.3 - Fabricating the Plasmonic Metamaterial

Fabrication of nanostructures with an FIB are generally produced on thick substrates, which means that the layer is very uniform and stable. The fabrication carried out here was of the rarer kind, on a 50nm freestanding layer of gold. Due to the sensitivity of the fabrication, the procedure is not trivial. Hence, in this subsection the different steps for the fabrication are explained followed with a discussion of the characterizations provided by microspectrophotometer measurements.

Step 1: The freestanding layer of gold - Fabrication quality depends on several factors, the first of which is the quality of the ultrathin freestanding layer of gold (provided by our collaborator Dr. Joao Valente). This factor is fully dependent on the thermal evaporation of the metallic layer and the reactive ion etching/dry etching recipe. A low quality freestanding layer can be observed during the FIB fabrication of nanostructures through the action of 'stretching' and 'wobbling' of

the surface. The act of stretching, portrayed in figures 3.10(a)-(c), is defined by straining lines that appear when pressure is applied to the 50nm thick metallic layer. This is similar to how aluminum foil sheets will show strain if pressure is applied.

Figure 3.10 - Low quality 50nm dry-etched Gold freestanding membranes displaying stretching.

An example of fabricating an asymmetric split-ring array in such conditions is shown in figure 3.10(d). By looking closely at the top row on the left hand side of the square array, a fabricated line of the array is shifted. This is indeed due to the wobbling of the freestanding layer during the sequential fabrication of the array. Hence, these membranes were completely unusable since the stretching also made the membrane's surface very uneven thus the focusing of the ions could never be optimized.

Step 2: Calibrating the focus - Once a high quality layer is obtained, such as the one imaged with the SEM in figure 3.11(a), the FIB's focusing parameters need to be carefully optimized. In order to produce structures with refined features the smallest aperture of the FIB is required. The drawback of focusing with an aperture size of 2 pA (picoAmperes) is rooted from the fact that the

contrast between being poorly focused and optimally focused is more challenging to distinguish since less electrons are imaging. Moreover, calibrating for too long will make a hole or create a tare through the freestanding layer.

Figure 3.11 - Map of a nanostructured high quality membrane (a) and in (b) zoom in of the lower right quadrant of the membrane. Framed in the short-dashed green line is the structure used for the experiment (SR5), framed in the dotted white line are the focusing calibrating $5\mu\text{m} \times 5\mu\text{m}$ structured arrays, and framed in the long-dashed red line is structure SR8 used for comparisons.

Thus, in order to calibrate the focus, small $5\mu\text{m} \times 5\mu\text{m}$ nanostructured arrays were fabricated, as illustrated in figure 3.11(b) in the white dotted rectangle (top right hand corner). These calibration nanostructures are fabricated then imaged. Based on the milling quality of the geometrical features, different focusing optimizations are performed. Needless to say, the first trial for calibration focusing is generally far from what the optimized structures will look like, as displayed in figure 3.12(a). We notice two flaws. First, the bottom horizontal slits are extremely large and very rounded which will affect the resonance-coupling of the antennas. Second, the ‘upside-down U’ component is not always milled properly, in turn, this will probably contribute to a higher reflection than the one desired. After several improvements of the focusing parameters, nine metamaterial arrays are fabricated. Of those nine, one matched the parameters. Indeed, structure SR5 in figure 3.12(b) is composed of very straight features for both the bottom horizontal slits and the ‘upside-down U’ components.

Step 3: Variation of parameters – Structure SR5 is one of nine structures that were fabricated with a variation of particular parameters of the FIB. The first varied parameter is the ‘current dose’ which dictates the amount of ions per unit

length in units of nC/cm (nanoCoulomb per centimeter). Typically, increasing that parameter will result in larger widths of the milled features. The second and the third parameters have to do with the horizontal and vertical distances (in units of nm) between the scanned points of the ion beam when it mills, namely the ‘center-to-center distance’ parameter and the ‘line spacing’ parameter, respectively. Decreasing these two parameters will provide more precision in the widths of the structures. Hence, high quality structures called for low current doses and low values for the center-to-center distance and line spacing. For the nine structures, the current dose was varied from 6.10 to 11.00 nC/cm, the center-to-center distance and line spacing were varied from 7.06 nm to 9.17 nm (all parameters can be found in the Appendix). For structure SR5, the set current dose was 6.40 nC/cm, and the set center-to-center distance and line spacing were 8.47 nm each.

Figure 3.12 - (a) SEM image from a low quality focusing regime with FIB and in (b) SEM image from a high quality focusing regime with FIB.

Characterizations - It is imperative to highlight that the metamaterial had to be fabricated by taking into account the superposition of polarization states and the eraser states. In other words, it was crucial for nanostructures to produce CPA in the horizontal, vertical and 45 degree polarizations. Consequently, for those three polarizations, reflections and transmissions were required to be equal to 25% and thus 50% absorption. The reason for such a condition originates from the fact that if our metamaterial transmitted more in one polarization than the other, the reflection equals to transmission requirement for CPA would not always be

satisfied. Moreover, the unbalanced metamaterial would be equivalent to a polarizer, for which distinguishability of optical paths would always occur and by association no CPA would ever take place. Therefore, our functioning metamaterial, structure SR5, was characterized at the wavelength of our entangled photons of 810nm by using a microspectrophotometer for which the normalized intensities of reflection, transmission and absorption are given for all three polarizations in table 1.

	H	V	45°
Reflection	~26%	~26%	~24%
Transmission	~29%	~29%	~30%
Absorption	~45%	~45%	~46%

Table 1 - structure SR5 values for 810nm optical reflection, transmission and absorption for the horizontal polarization H, the vertical polarization V and the 45 degree polarization 45°.

The above values were retrieved from the spectra taken for a wavelength range of $\lambda= 500 \text{ nm} - 1500\text{nm}$, depicted below in figure 3.13. We observe that for all three polarizations (solid lines, dashed lines and dotted lines) **reflection** is the same value of ~26% except for the 45° polarization state that varies by ~2%. Similarly, **transmission** for all three polarizations remains the same with a value of ~29% except for the 45° polarization state that varies by ~1%. And **absorption** for all three polarizations stands at ~45% and ~46%. Thus, in agreement with the previously mentioned requirement for reflection and transmission to produce coherent perfect absorption with polarization entangled photons, we observe that although the transmission is slightly greater (3-6%) than reflection for all three polarizations, their values should still be compatible for our quantum eraser experiment. In the figure below we also discern noise occurring at the 900nm wavelength. This feature is due to the switch of detectors in the microspectrophotometer from the silicon detector (efficient for 200nm to 900nm) to the InGaAs photodiode (efficient for 750nm to 1600nm). Thus it is completely independent of the metamaterial nanostructures.

Figure 3.13 - The SR5 preferred structure's reflection (orange), transmission (blue) and absorption (green) spectra produced with the microspectrophotometer for the horizontal polarization (solid line), the vertical polarization (dashed line) and the +45 polarization (dotted line). The red vertical line represents the 810nm wavelength of our photons. The noise observed at 900nm are due to the switch of detectors in our microspectrophotometer.

Another set of characterization measurements is needed though to assess if the reflection levels on both sides are equivalent. Indeed, optimal visibility of coherent perfect absorption is only achievable in the case where photons are reflected by the same amount from both sides of the metamaterial. Thus, the previous spectra measured with light incident from the thermally evaporated gold side of the sample is compared with the spectra obtained with the beam incident from the etched side of the sample as illustrated in figure 3.14. The figure shows a drawing of two reflections represented by orange curved arrows and two transmissions represented by blue straight arrows. The sample, illustrated by the yellow rectangle, has two sides: an etched side (left) underlined by a slight surface roughness due to the imperfections caused by the reactive ion etching process and the gold side (right) pictured with a smoother surface. Below, the spectra for each polarization compares the reflection (orange curves), transmission (blue curves) and absorption (green curves) for light incident on the gold side (dashed curves) and light incident on the etched side (solid curves). The minor differences between the reflections from both sides speak to the quality of etching both in surface roughness and in the total removal of the Silicon Nitride membrane. Furthermore, it is common knowledge that transmission through the metamaterial should be the same from both sides which is observed from reduced

differences between transmissions as compared to the differences between reflections (from both sides). We notice that for 810nm, marked by a red vertical line, reflection and transmission from the etched side for all three polarizations still intersect at the intensity of ~25%.

Figure 3.14 - Structure SR5 comparison of optical properties for light incident from opposite sides of the sample. The reflection is denoted by the orange curves, the transmission is denoted by the blue curves and the absorption is denoted by the green curves for horizontally polarized light (left), vertically polarized light (middle) and 45 degree polarized light (right). The red vertical line designates the 810nm wavelength of our photons. The noise observed at 900nm are due to the switch of detectors in our spectrometer.

For the sake of underlining the particular properties of the optimized metamaterial structure SR5, what follows compares it with the metamaterial structure SR8, defined as a nanostructured array that does not comply with the desired balanced reflection and transmission intensities for the three polarization states. Since we have already established for structure SR5 that the reflections and transmissions were the same for light incident from both sides, we formalize the spectra by solely showing the results for reflections and transmissions incident from the gold side. By studying the spectra of SR8 in figure 3.15, we conclude that seemingly, only the vertical polarization would produce coherent perfect absorption for photons of 810nm in wavelength. This is noticeable due to the intersection of reflection and transmission for the vertical polarization being superposed with the vertical red line, indicator of the 810nm wavelength at an intensity of approximately 25%. The appropriate polarization state for CPA is

also conveyed through table 2 that lists the reflections, transmissions and absorptions of the structure SR8.

	H	V	45°
Reflection	~46%	~24%	~43%
Transmission	~14%	~28%	~20%
Absorption	~40%	~48%	~37%

Table 2 - Structure SR8 values for 810nm optical reflection, transmission and absorption for the horizontal polarization H, the vertical polarization V and the 45 degree polarization 45°.

We analyze the measured values yielded by structure SR8 in the above table in the same manner as for the values for structure SR5 in table 1, whereby we first compare the different polarization-specific values for each optical property (reflection, transmission and absorption). Then, we compare the reflection and transmission values for each polarization. In other words, the first comparison method will speak to the polarization dependence of metamaterial and the second comparison method will speak to the quality of CPA for different polarizations. Thus, for table 2, we observe that for all polarizations the **reflections** are not the same value. The horizontal polarization (H) and the 45 degree polarization (45°) have nearly equivalent values of ~46% and ~43%. On the other hand, the vertical polarization (V) results in a lower reflection of ~24%. Therefore, we note that the reflections for the horizontal polarization and the 45 degree polarization are approximately twice that of the reflection in the vertical polarization. Quite the opposite occurs for **transmission** even though values of different polarizations are still not unbalanced. More specifically the vertical polarization (V) yields a greater value of ~28%, while the 45 degree and horizontal polarizations result in lower values of ~20% and ~14% respectively. As a by-product, calculating **absorption** yields a value of ~48% for the vertical polarization (V), and results in neighboring values of ~40% and ~37% for the horizontal polarization (H) and the 45 degree polarization (45°). Thus, we observe very different values for different polarizations in reflection, transmission and absorption, which indicates

that CPA would not be present in all three polarization states. Despite the fact that different polarizations are unbalanced, by way of the second comparison method, we observe that the vertical polarization state (V) would provide coherent perfect absorption due to the corresponding balanced values for reflection and transmission being in the neighborhood of 25%. This means that if my single photons were in a vertical polarization state, coherent perfect absorption would occur. On the other hand, if they were in a horizontal polarization state or a 45 polarization state, very low visibility of CPA would be observed. Using that metamaterial would seriously impair our ability to revive CPA through quantum erasing for both the local and nonlocal cases, more of which will be explained in the next sections.

Figure 3.15 - Structure SR8 from the gold side. The reflection is denoted by the orange curves, the transmission is denoted by the blue curves and the absorption is denoted by the green curves for horizontally polarized light (left), vertically polarized light (middle) and 45 degree polarized light (right). The red vertical line designates the 810nm wavelength of our photons. The noise observed at 900nm are due to the switch of detectors in our spectrometer.

A parallel can be drawn regarding this plasmonic metamaterial in relation to its compatibility in the three polarization states. It is an established fact that all polarization states can be defined in terms of a horizontal and a vertical component of the form $\cos(\theta)|H\rangle + \sin(\theta)|V\rangle$, where $\theta = 0^\circ$ for the horizontal polarization and $\theta = 90^\circ$ for the vertical polarization. Thus, if both the horizontal and the vertical polarization states absorb, reflect and transmit by the same amount, an assumption may be stated that photons in any polarization state will be reflected, transmitted and absorbed by the same amount. Indeed, this statement is verified experimentally in figure 3.16 below for our optimized structure SR5 and compared with our poorly coherently absorbing structure SR8.

Figure 3.16 - Polarization variation optical properties. Reflection (orange), transmission (blue) and absorption (green) for different polarization states with a 10 degrees incrementation.

We notice that for our optimized metamaterial SR5, reflection, transmission and absorption barely endures any change in intensity and in fact, this shows that our metamaterial has the potential of producing CPA in any polarization state. Oppositely, we observe from the spectra of structure SR8 that both reflection and transmission endure a change in intensity of $\sim 22\%$ and $\sim 24\%$ respectively. Interestingly enough, by virtue of investigating polarization angle dependence, reflection and transmission intersect at one point in between the 70° and 80° polarization states. Incidentally this study of optical properties for different polarization states emphasizes the polarization dependence but also indicates the polarization state for which CPA would be optimized.

Therefore, with the full description of the fabrication process in the development of a highly optimized absorber, the next section explains the reasoning behind designing a nanostructured array that produces CPA for the horizontal, vertical

and 45° polarization states by first describing the experimental quantum eraser interferometer optical apparatus.

3.3.4 - The Quantum Eraser Interferometer Optical Apparatus

As mentioned and illustrated previously in figure 3.9, the quantum eraser interferometer has two optical paths, which under certain conditions are distinguishable. For instance, in the apparatus used for the theory of the quantum eraser discussed in section 3.3.2, the paths were distinguishable in polarization with one polarizer in each optical path. The polarizers effectively labelled each path by transmitting orthogonal states for which a polarization-specific measurement at the output could provide the observer with the ‘which-path information’ (WPI).

In our quantum eraser depicted in figure 3.17, the polarizers were replaced by a single half-wave plate (HWP A) aligned in optical path A. The half-wave plate’s fast axis was positioned with an angle of 45 degrees (or $\pi/4$) relative to the horizontal plane of the interferometer. Consequently, since half-wave plates rotate the polarization of a transmitted photon by a factor of two times the angle between the fast axis and the polarization of the incident photons, a vertical polarization (or a horizontal polarization) will develop into a horizontal polarization (or a vertical polarization).

Figure 3.17 - Illustration of quantum eraser interferometer. Path I from the entangled source is guided to the interferometer with single mode optical fibers. The photons are then collimated through a collimation lens (CL). To compensate for the optical fiber effects on polarization, a combination of a quarter-wave plate (QWP), half-wave plate (HWP), flip mirror (FM) and polarizer (P) are used. The metamaterial is aligned with a 808nm continuous wave laser and imaged with the CCD camera.

Consequently, if a vertical polarized photon $|V\rangle$ (or horizontal polarized photon $|H\rangle$) is incident on beamsplitter BS1, it will be reflected onto optical path B with 50% probability and interact with the metamaterial MM as a vertical polarized photon $|V\rangle$ (or horizontal polarized photon $|H\rangle$). Alternatively, with 50% probability, it will be transmitted through beamsplitter BS1 and proceed onto path A through half-wave plate HWP A incidentally reaching the metamaterial MM in a horizontal polarization $|H\rangle$ (or vertical polarization $|V\rangle$).

At this point, a photon that traveled in optical path B (or A) will either be transmitted, reflected or absorbed by the freestanding metamaterial MM. In the event it is reflected or transmitted, one of two couplers denoted 'C' and 'D' will detect it.

The alignment procedure consisted in centering the optical paths on the chosen $30\mu\text{m} \times 30\mu\text{m}$ nanostructured array with a 3mW continuous wave laser of 808nm in wavelength and a white light source to illuminate the membrane. The laser is introduced into the interferometer by using a single mode fiber coupled to the

input collimator used for the single photons from path I of our SPDC source. The alignment beam is then centered onto the metamaterial array by reflecting the output from beamsplitter BSB with a flipped up mirror CCD-FM to a CCD camera. This particular technique was also used to verify the optical parameters of the different asymmetric split-ring arrays as a function of visibility. We then reproduced the results for the quantum eraser with the alignment beam.

We observed that indeed, hinting to the quantum regime, for the case of vertical and horizontal polarized photons, information about the photon may be revealed by cause of polarization-dependent optical paths. As a by-product, absence of interference will occur and by association, no coherent perfect absorption can be achieved.

However, a coherent perfect absorption regime can be recovered by using polarizers to either perform a “post-selective” measurement or a “pre-selective” measurement. For the case of a “post-selective” measurements, which is used in our ‘local’ quantum eraser CPA, polarizers are placed in front of the output couplers C and D of the interferometer and the polarizer in optical path II is removed. By virtue of measuring the $|+45\rangle$ and $|-45\rangle$ polarization states, which we call the ‘eraser states’, coherent perfect absorption is recovered. On the other hand, for the case of a “pre-selective” measurements, specific to our ‘nonlocal’ CPA, polarizers at the output couplers C and D of the interferometer are removed and a polarizer is placed in optical path II. As a result of measuring the ‘eraser states’ nonlocally in path II, the orthogonal ‘eraser states’ will be projected onto the photons in the interferometer, thus a coherent perfect absorption regime is produced. In the following sections, the local “post-selective” quantum eraser CPA will be presented and subsequently followed by the nonlocal “pre-selective” quantum eraser CPA.

3.3.5 - The Local Quantum Eraser CPA

As outlined above, a coherent perfect absorption regime can be recovered in a quantum eraser interferometer by either conducting a “post-selective” measurement or a “pre-selective” measurement. The local quantum eraser CPA corresponds to the former configuration, where measurements on the polarization are only produced at the output of the interferometer. This section is organized by first providing the theoretical description of the experiment, which is useful in highlighting particular quantum optical aspects of the apparatus. Second to that, the experimental details and a discussion based on the results are presented.

3.3.5.1 - The Theory

In order to provide the theoretical description, the wavefunction for the optical apparatus needs to be defined. From the illustrated optical setup in figure 3.17, we deduce that both polarization entanglement from our SPDC source and path entanglement from within the interferometer are used, depicted in equations 3.15 and 3.16 respectively.

$$|\Psi\rangle = \frac{1}{\sqrt{2}} (|H\rangle_I |V\rangle_{II} - |V\rangle_I |H\rangle_{II}) \quad [3.15]$$

$$|\Psi\rangle = \frac{1}{\sqrt{2}} (|1\rangle_A |0\rangle_B + e^{i\phi} |0\rangle_A |1\rangle_B) \quad [3.16]$$

We combine both types of entanglements by substituting the number state $|1\rangle$ by the polarization state associated to each path A and B. This is done by taking into account that the half-wave plate HWP A rotates a horizontal polarization state $|H\rangle_A$ to the vertical polarization state $|V\rangle_A$ and vice-versa. Hence, for the case of an incident horizontal polarization or vertical polarization we obtain equations 3.17 and 3.18, respectively.

$$|\Psi\rangle = \frac{1}{\sqrt{2}} (|V\rangle_A |0\rangle_B + e^{i\phi} |0\rangle_A |H\rangle_B) \quad [3.17]$$

$$|\Psi\rangle = \frac{1}{\sqrt{2}} (|H\rangle_A |0\rangle_B + e^{i\phi} |0\rangle_A |V\rangle_B) \quad [3.18]$$

We then incorporate them in the polarization entanglement wavefunction for each state of the photons from path I. Since in this local quantum eraser CPA the polarizers are placed in front of the output couplers C and D, we define the wavefunction in terms of both outputs, denoted $|\Psi_C\rangle$ and $|\Psi_D\rangle$ in equation 3.19. It is also important to note that in the formulations presented below, since mirrors MA and MB add the same phase to path A and path B of $e^{i\pi/4}$, they compensate each other in relative phase and hence do not need to be part of the wavefunction expressions. In contrast, as a result of the asymmetry in phase created by the reflection on the beamsplitter BS1, a phase factor of i is produced for photons in path B.

$$\begin{aligned} |\Psi\rangle = & \frac{1}{\sqrt{2}} [(\sqrt{a_R}|V\rangle_A |0\rangle_B |\Psi_C\rangle + ie^{i\phi} \sqrt{b_T}|0\rangle_A |H\rangle_B |\Psi_C\rangle \\ & + \sqrt{a_T}|V\rangle_A |0\rangle_B |\Psi_D\rangle + ie^{i\phi} \sqrt{b_R}|0\rangle_A |H\rangle_B |\Psi_D\rangle) |V\rangle_{II} \\ & - (\sqrt{a_R}|H\rangle_A |0\rangle_B |\Psi_C\rangle + ie^{i\phi} \sqrt{b_T}|0\rangle_A |V\rangle_B |\Psi_C\rangle \\ & + \sqrt{a_T}|H\rangle_A |0\rangle_B |\Psi_D\rangle + ie^{i\phi} \sqrt{b_R}|0\rangle_A |V\rangle_B |\Psi_D\rangle) |H\rangle_{II}] \end{aligned} \quad [3.19]$$

Since the photon will either reflect or transmit, the normalization factors used (in bold in equation 3.19) represent the level of reflection and transmission of the metamaterial. By expanding with the nonlocal polarization state and by projecting on each detector, we obtain a three state superposition comprised of a $|V\rangle$, $|H\rangle$, or $|0\rangle$ polarization state for interferometer paths A, B and a nonlocal path II (for which path II is never $|0\rangle$) (equations 3.20 and 3.22).

$$\begin{aligned} \langle\Psi_C|\Psi\rangle = & \frac{1}{\sqrt{2}} (\sqrt{a_R}|V\rangle_A |0\rangle_B |V\rangle_{II} + ie^{i\phi} \sqrt{b_T}|0\rangle_A |H\rangle_B |V\rangle_{II} - \\ & \sqrt{a_R}|H\rangle_A |0\rangle_B |H\rangle_{II} - ie^{i\phi} \sqrt{b_T}|0\rangle_A |V\rangle_B |H\rangle_{II}) \end{aligned} \quad [3.20]$$

$$\begin{aligned} \langle\Psi_D|\Psi\rangle = & \frac{1}{\sqrt{2}} (\sqrt{a_R}(|V\rangle_A |0\rangle_B |V\rangle_{II} - |H\rangle_A |0\rangle_B |H\rangle_{II}) \\ & + ie^{i\phi} \sqrt{b_T}(|0\rangle_A |H\rangle_B |V\rangle_{II} - |0\rangle_A |V\rangle_B |H\rangle_{II})) \end{aligned} \quad [3.21]$$

$$\langle \Psi_D | \Psi \rangle = \frac{1}{\sqrt{2}} (\sqrt{a_T} |V\rangle_A |0\rangle_B |V\rangle_{II} + ie^{i\phi} \sqrt{b_R} |0\rangle_A |H\rangle_B |V\rangle_{II} - \sqrt{a_T} |H\rangle_A |0\rangle_B |H\rangle_{II} - ie^{i\phi} \sqrt{b_R} |0\rangle_A |V\rangle_B |H\rangle_{II}) \quad [3.22]$$

$$\langle \Psi_D | \Psi \rangle = \frac{1}{\sqrt{2}} (\sqrt{a_T} (|V\rangle_A |0\rangle_B |V\rangle_{II} - |H\rangle_A |0\rangle_B |H\rangle_{II}) + ie^{i\phi} \sqrt{b_R} (|0\rangle_A |H\rangle_B |V\rangle_{II} - |0\rangle_A |V\rangle_B |H\rangle_{II})) \quad [3.23]$$

By extension, the wavefunctions can be represented in the form of a path-entangled wavefunction by factoring out the normalization constants and the relative phase component as shown for coupler C in equation 3.21 and coupler D in equation 3.23. Under this wavefunction structure, we observe that for a metamaterial that satisfies reflection = transmission on both sides, more specifically in alignment with the relations below (equation 3.24), we obtain a simplified form where both output probability amplitudes are equal (equation 3.25).

$$\sqrt{a_T} = \sqrt{b_T} = \sqrt{a_R} = \sqrt{b_R} = \sqrt{0.25} \quad [3.24]$$

$$\langle \Psi_C | \Psi \rangle = \langle \Psi_D | \Psi \rangle = \frac{1}{\sqrt{2}} \cdot \sqrt{0.25} ((|V\rangle_A |0\rangle_B |V\rangle_{II} - |H\rangle_A |0\rangle_B |H\rangle_{II}) + ie^{i\phi} (|0\rangle_A |H\rangle_B |V\rangle_{II} - |0\rangle_A |V\rangle_B |H\rangle_{II})) \quad [3.25]$$

Hence, to reduce the derivations, a wavefunction $|\Psi_{Out}\rangle = \langle \Psi_C | \Psi \rangle = \langle \Psi_D | \Psi \rangle$ is produced. Further, for simplicity we set the relative phase $\Phi = \phi + \pi/2$, since $i = e^{i\pi/2}$. In this way, the general output wavefunction for coupler C or coupler D is represented below in equation 3.26.

$$|\Psi_{Out}\rangle = \frac{1}{\sqrt{2}} \cdot \sqrt{0.25} ((|V\rangle_A |0\rangle_B |V\rangle_{II} - |H\rangle_A |0\rangle_B |H\rangle_{II}) + e^{i\Phi} (|0\rangle_A |H\rangle_B |V\rangle_{II} - |0\rangle_A |V\rangle_B |H\rangle_{II})) \quad [3.26]$$

Therefore, the sum of detection probabilities of both outputs will be twice the detection probability of $|\Psi_{Out}\rangle$,

$$||\Psi_{Total}\rangle|^2 = 2 \cdot ||\Psi_{Out}\rangle|^2 \quad [3.27]$$

On that account, local measurements on the quantum eraser CPA scheme with entangled photons are derived. Erasing or lack thereof is conducted with

polarizers at the output of the interferometer. They project a polarization state on both paths A and B. Having underlined previously in equation 3.25 that the probability amplitudes of both outputs are equal, the standard used for the derivations have been formulated with respect to one output only. This formality is established due to the fact that erasing of one output always results in erasing of the other output. Hence, we first consider the case for which the polarizers transmit $|H\rangle$ and $|V\rangle$ in equation 3.28 and 3.29.

$$\langle H|\Psi_{\text{Out}}\rangle = 1/\sqrt{2} \cdot \sqrt{0.25}((-|0\rangle_B|H\rangle_{\text{II}}) + e^{i\Phi}(|0\rangle_A|V\rangle_{\text{II}})) \quad [3.28]$$

$$\langle V|\Psi_{\text{Out}}\rangle = 1/\sqrt{2} \cdot \sqrt{0.25}(|0\rangle_B|V\rangle_{\text{II}}) + e^{i\Phi}(|0\rangle_A|H\rangle_{\text{II}}) \quad [3.29]$$

We notice that for both wavefunctions measured for the horizontal and the vertical polarizations, two superpositions of two states remain. One of two states for each superposition belongs to the nonlocal photon in path II. The other state of each superposition is always a ‘zero’ state ($|0\rangle$) describing the absence of photons for a particular path A or B, which is equivalent to indicating the presence of photons for a particular path B or A, respectively. Moreover, within each wavefunction we notice that the zero states of the superpositions are always relative to two different optical paths. And, in relation to distinguishability, for each wavefunction, each zero state is superposed with a different nonlocal state of either $|H\rangle$ or $|V\rangle$. Therefore, the observer in this case is able to obtain the ‘which-path information’ (WPI) by measuring the nonlocal photon of the pair in the horizontal/vertical basis. This type of WPI was first introduced in the work by Pysher *et al.* [33] and referred to as ‘nonlocal labeling of paths’. The ‘labeling’ is a purely nonlocal effect that refers to the availability of WPI through correlations of non-classical photon pairs. For instance, for a local polarizer transmitting $|H\rangle$ and a nonlocal polarizer in optical path II set to transmit $|H\rangle$ or $|V\rangle$ yields, as shown in equations 3.30 and 3.31, a WPI that the photon is in path A or in path B, respectively (since it is not in path B or A, respectively). The same goes for a local polarizer transmitting $|V\rangle$, for which the WPI is confirmed in equations 3.32 and 3.33.

$$\langle H|_{\text{II}}\langle H|\Psi_{\text{Out}}\rangle = 1/\sqrt{2} \cdot \sqrt{0.25}(-|0\rangle_B) \quad [3.30]$$

$$\langle V|_{II} \langle H|\Psi_{Out}\rangle = 1/\sqrt{2} \cdot \sqrt{0.25} (e^{i\Phi} |0\rangle_A) \quad [3.31]$$

$$\langle H|_{II} \langle V|\Psi_{Out}\rangle = 1/\sqrt{2} \cdot \sqrt{0.25} (e^{i\Phi} |0\rangle_A) \quad [3.32]$$

$$\langle V|_{II} \langle V|\Psi_{Out}\rangle = 1/\sqrt{2} \cdot \sqrt{0.25} (|0\rangle_B) \quad [3.33]$$

In consequence, the evidence of WPI confirms that an entangled photon **locally** measured in the horizontal or vertical polarization state does not interfere with itself. On the other hand, when the local polarizer is set to transmit the $|+45\rangle$ or $|-45\rangle$ polarization state defined in equations 3.34 and 3.35, the optical paths in the interferometer will no longer be distinguishable as shown below in equation 3.36 for the $|+45\rangle$ polarization state (naturally erasing occurs for the $|-45\rangle$ polarization state as well). A simplified version of the projection is formulated in equation 3.37, where we observe that the nonlocal photon ‘labels’ both paths in the same polarization state, thus the WPI is no longer available to the observer, and by association, the single photon will interfere with itself, and consequently coherent perfect absorption occurs.

$$|+45\rangle = 1/\sqrt{2} (\pm|H\rangle \pm |V\rangle) \quad [3.34]$$

$$|-45\rangle = 1/\sqrt{2} (\pm|H\rangle \mp |V\rangle) \quad [3.35]$$

$$\begin{aligned} \langle +45|\Psi_{Out}\rangle = & 1/\sqrt{2} \cdot \sqrt{0.25} ((1/\sqrt{2} |0\rangle_B |V\rangle_{II} - 1/\sqrt{2} |0\rangle_B |H\rangle_{II}) \\ & + e^{i\Phi} (1/\sqrt{2} |0\rangle_A |V\rangle_{II} - 1/\sqrt{2} |0\rangle_A |H\rangle_{II})) \end{aligned} \quad [3.36]$$

$$\langle +45|\Psi_{Out}\rangle = 1/\sqrt{2} \cdot \sqrt{0.25} (|0\rangle_B |-45\rangle_{II} + e^{i\Phi} |0\rangle_A |-45\rangle_{II}) \quad [3.37]$$

Concurrently, in parallel with the local measurement on $|H\rangle$ and $|V\rangle$, we verify that under no condition the WPI is available for a local $|+45\rangle$ measurement. We do so by projecting polarizations $|H\rangle$, $|V\rangle$ and $|-45\rangle$ on the nonlocal optical path II. First, we analyze equations 3.38 and 3.39 that describe the cases when the polarizer in the polarization-entangled path II is set to transmit the horizontal or

vertical polarizations. Opposite to the previous cases, when making these measurements created distinguishability, thus absence of interference and therefore no coherent perfect absorption/transmission, in this case, the optical paths A and B are indistinguishable, and more importantly, a regime favorable to coherent perfect absorption and coherent perfect transmission is created.

In a similar manner, we observe evidence of erasing with the nonlocal polarizer set to transmit the $|-45\rangle$ polarization state (equation 3.40) which confirms that no nonlocal measurement can allow the observer to get the WPI.

$$\langle H_{II} | \langle +45 | \Psi_{\text{Out}} \rangle = 1/2 \cdot \sqrt{0.25} (-|0\rangle_B - e^{i\Phi} |0\rangle_A) \quad [3.38]$$

$$\langle V_{II} | \langle +45 | \Psi_{\text{Out}} \rangle = 1/2 \cdot \sqrt{0.25} (|0\rangle_B + e^{i\Phi} |0\rangle_A) \quad [3.39]$$

$$\langle -45_{II} | \langle +45 | \Psi_{\text{Out}} \rangle = 1/\sqrt{2} \cdot \sqrt{0.25} (|0\rangle_B + e^{i\Phi} |0\rangle_A) \quad [3.40]$$

Furthermore, I would like to underline the difference between the normalization factor of $1/2$ in equations 3.38 and 3.39, and the normalization factor of $1/\sqrt{2}$ in equation 3.40. In the former, we are projecting the horizontal or the vertical polarizations on the $|-45\rangle$ states constituting the wavefunction in equation 3.37. Hence, projecting the horizontal polarization $|H\rangle$ or the vertical polarization $|V\rangle$ on the $|-45\rangle$ polarization (defined in equation 3.35) will yield an additional factor of $1/\sqrt{2}$ which will be multiplied by the existing path-entanglement normalization factor of $1/\sqrt{2}$ and result in a factor of $1/2$ (see equations 3.41 and 3.42). In contrast, the latter projects the -45 polarization on the $|-45\rangle$ states constituting the wavefunction, which equals to 1 (see equation 3.43), thus explaining the $1/\sqrt{2}$ normalization factor in equation 3.40. It is important to underline that this factor although present in the probability amplitude has no effect on conservation of entanglement rather it is path or polarization-specific, it only contributes to the numerical value of the detection probability.

$$\langle H | -45 \rangle = \begin{pmatrix} 1 & 0 \end{pmatrix} \begin{pmatrix} \pm 1/\sqrt{2} \\ \mp 1/\sqrt{2} \end{pmatrix} = \pm 1/\sqrt{2} \quad [3.41]$$

$$\langle V|-45\rangle = (0 \quad 1) \begin{pmatrix} \pm 1/\sqrt{2} \\ \mp 1/\sqrt{2} \end{pmatrix} = \mp 1/\sqrt{2} \quad [3.42]$$

$$\langle -45|-45\rangle = (\pm 1/\sqrt{2} \quad \mp 1/\sqrt{2}) \begin{pmatrix} \pm 1/\sqrt{2} \\ \mp 1/\sqrt{2} \end{pmatrix} = 1 \quad [3.43]$$

As a result of defining the proper state to measure locally in order to allow the single entangled photon to interfere with itself through erasing the WPI, we now compute the probability of detection which is expressed as the modulus square of the obtained probability amplitude in equation 3.37. We recall though that we only obtained the result specific to one output of the interferometer, as highlighted previously, therefore the probability of detection produced in equation 3.45 is multiplied by a factor of two in order to get the sum of the joint detection probabilities formulated in equation 3.46. Subsequently, by changing the relative phase Φ value from π to 2π , the detection probability yields 0 for CPA and unitary for CPT, respectively (equations 3.47, 3.48), in agreement with previous published results on coherent absorbers.

$$|\langle +45|\Psi_{\text{Out}}\rangle|^2 = 1/2 \cdot |1/2 (1 + e^{i\Phi})|^2 \quad [3.44]$$

$$|\langle +45|\Psi_{\text{Out}}\rangle|^2 = 1/2 \cdot \cos^2(\Phi/2) \quad [3.45]$$

$$|\langle +45|\Psi_{\text{Total}}\rangle|^2 = 2 \times |\langle +45|\Psi_{\text{Out}}\rangle|^2 = \cos^2(\Phi/2) \quad [3.46]$$

Coherent perfect absorption $\rightarrow \Phi = \pi$:

$$|\langle +45|\Psi_{\text{Total}}\rangle|^2 = 0 \quad [3.47]$$

Coherent perfect transmission $\rightarrow \Phi = 2\pi$:

$$|\langle +45|\Psi_{\text{Total}}\rangle|^2 = 1 \quad [3.48]$$

Hence, this theoretical formulation highlights two particular points. The first point is that when the WPI is discovered by the observer it is not done locally, as would be expected for a single photon experiment, but non-locally through nonlocal labelling of paths. The second point originates from the capacity to produce a post-selective measurement in order to revive or destroy CPA in a quantum eraser interferometer.

3.3.5.2 - The Experiment and the Results

Figure 3.18 - Top left: the coincidence counting module receiving single photon counts from single photon detectors. Coincidences are counted between outputs of interferometer C and D, and the output coupler in path II of the entangled source.

As depicted in figure 3.18, photons from path I of the polarization entangled source (bottom left) is introduced into the interferometer through a single mode fiber. Since our experiment will make use of the linear polarization of the photons from path I for quantum erasing, a quarter-wave plate (QWP) and half-wave plate (HWP) recover the initial polarization state generated at the source. The calibration is done by placing a polarizer PI in front of the entangled source's coupler in path I. By setting PI to the horizontal polarization $|H\rangle$, only that polarization will enter the single mode optical fiber. Hence, due to the fact the optical fiber's output is coupled into the interferometer, for the purpose of conserving the initial polarization state of the photon at the source, only horizontal polarized $|H\rangle$ photons should be present at the output of the fiber. In order to verify this condition, a mirror denoted 'FM' in figure 3.17 is flipped up and reflects light to a coupler. When the polarizer P (illustrated in figure 3.17), is

set to transmits only the orthogonal polarization $|V\rangle$ and is placed in the optical path to the coupler used for calibration (right below mirror MB in the figure), a single photon count close to zero indicates that the polarization state in the interferometer is identical to that of the photon transmitted through polarizer PI in path I in the polarization entangled source. Due to particular polarization-specific effects related to cylindrical-like shaped media in optical fibers [34, 35, 36], the polarization is generally not conserved at the fiber core's output. In that case, the polarization state needs to be recovered with the quarter-wave plate QWP and the half-wave plate HWP depicted in figure 3.17. In this calibration scheme, the quarter-wave plate QWP is used to recover a linear polarization and the half-wave plate HWP recovers the angle of the polarization. Thus, if the polarization has gained in phase in the optical fiber, linear polarization is recovered by measuring all polarization states with polarizer P for each phase compensation of the quarter-wave plate QWP until a single photon count close to zero is obtained. Once the phase is fully compensated for, the half-wave plate HWP is rotated to fully recover the polarization state of each photon both in phase and angle. This 'polarization calibration test' was conducted for the $|H\rangle$, $|V\rangle$, $|+45\rangle$, and $|-45\rangle$ polarization states before and after acquiring our CPA-related results. In the absence of running this test, experimental data may yield low visibility of coherent absorption as a result of a nonzero phase and/or a geometrical rotation of the polarization state.

In addition to recovering the polarization state of the entangled photons with the 'polarization calibration test', a Bell measurement was conducted to certify that the nonlocal quantum properties of the photons were still valid. In this case, for each fixed polarization measurement of polarizer P, namely $|H\rangle$, $|V\rangle$, $|+45\rangle$, and $|-45\rangle$, polarizer P2 produced sequential measurements from 0° to 180° with an increment of 5° .

As described above, the interferometer was authenticated before and after every sequence of measurements with the 'polarization calibration test' and a Bell measurement, which we refer to as the 'Bell measurement calibration test'. Since the successful calibration of the polarization with these tests only gives

information about the polarization in the interferometer up to the flip mirror FM (see figure 3.17), the conservation of polarization from the flip mirror FM to the couplers C and D was verified. This test was conducted with the 808nm unpolarized alignment laser for which a polarizer was placed in front of beamsplitter BS1 and another polarizer was placed in front of each output coupler C and D. Much like the ‘polarization calibration test’, the polarizer in front of BS1 is set to transmit a specific linear polarization, while the polarizers in front of couplers C and D are set to transmit the orthogonal polarization. For all four polarization states previously mentioned ($|H\rangle$, $|V\rangle$, $|+45\rangle$, $|-45\rangle$), namely the ‘basis set’, the detected intensity was near zero.

Thus, with the previously described full characterization of the interferometer and with the polarization compensation of the optical fiber’s added phase and geometrical rotation, the last task was to find an optimized nanostructured array for which the optical properties were the same for the horizontal and vertical polarizations. After testing the visibility of coherent perfect absorption for nine nanostructured arrays (shown in figure 3.11(b)) in all polarization states of the ‘basis set’, one array displaying ~90% visibility throughout was selected (structure SR5 in SEM image in figure 3.12(b)).

The structures were tested in a configuration for which HWP A was not rotating the polarization. In that manner, the optical apparatus was the same as for the experiment on coherent perfect absorption of a single photon [37] (figure 3.7 in section 3.2.2). The recorded modulation of absorption produced with the fabricated and optimized metamaterial in the interferometer is displayed in figure 3.19a in the form of blue hollow circular markers and a blue dotted fitted curve. The data shows the sum of coincidence counts as a function of relative phase produced by changing the position of the metamaterial mounted on a piezoelectric actuator. We observe a coherent absorption regime of ~500 coincidences per second (cps) and a coherent transmission regime of ~2400 cps. Furthermore, we highlight the relevance of the plasmonic nanostructured asymmetric split ring array in figure 3.19a with the absence of coherent perfect absorption when the metamaterial is replaced by unstructured gold (red hollow diamond markers).

In the interest of producing distinguishability of optical paths for coherent perfect absorption, the experiment was conducted with HWP A's fast axis positioned 45° to the horizontal plane. As discussed previously, in this situation the half-wave plate will rotate an incident horizontal polarization (or vertical polarization) to a vertical polarization (or horizontal polarization). As a result, the absence of modulation of absorption devised by the green square-shaped hollow markers in figure 3.19a confirmed that indeed, based on the quantum mechanical interpretation of interference of path entangled single photons, no interference occurs. Moreover, by extension, in the case of absorbing materials, since coherent perfect absorption is only produced with the existence of interference, path distinguishability will also result in the absence of coherent perfect absorption.

Figure 3.19 - (a) CPA with: the plasmonic metamaterial (exp:blue hollow circular markers,fit:blue dotted curve); unstructured gold (exp:red hollow diamond markers, fit:solid red line); the metamaterial and HWP A (exp:green hollow square markers fit: solid green line). (b) Local quantum erasing of CPA with polarizers at the output set to the 45 polarization (exp: blue filled circular markers, fit: blue dotted curve), the vertical polarization (exp: red filled diamond markers, fit: solid red line) and the horizontal polarization (exp: green filled square markers, fit: solid green line).

The demonstration described above underlines that HWP A's geometrical rotation of superposed orthogonal polarization states does not present a context that favors coherent perfect absorption. Thus, recovering a coherent perfect absorption regime is investigated by virtue of a “post-selective” measurement.

In this measurement, two polarizers are placed in front of output couplers C and D (figure 3.18). As illustrated in figure 3.19(b), in the event both polarizers are set to the horizontal polarization or vertical polarization, the experimental results represented by the green square markers and red diamond markers respectively demonstrate that no coherent perfect absorption takes place. The difference in average coincidence counts for different positions of the piezoelectric stage can be contributed to the metamaterial slightly absorbing more in the vertical polarization than in the horizontal polarization.

On the other hand, as illustrated by the blue filled circular markers, if both polarizers at the outputs are set to the 45 degree polarization, then coherent perfect absorption can be produced. In this situation, the ‘eraser state’ is not providing WPI to the observer, in agreement with the previous theoretical description, thus the path-entangled photons interfere. These experimental results therefore show that local measurements can enable or disable CPA.

Thus, in this section we investigated both theoretically and experimentally quantum coherent perfect absorption of entangled single photons in the setting of a quantum eraser interferometer. This first type of quantum eraser CPA is operated by way of conducting local measurements. In the next section, we present the second type of quantum eraser CPA for which we exploited the unique nonlocal properties of polarization entangled photon pairs in view of erasing the WPI and enabling CPA.

3.3.6 - Nonlocal Coherent Perfect Absorption

A nonlocal analog of the local quantum eraser CPA is presented here. In the local case, polarizers are placed at the output of the interferometer and measure different polarization states. When the polarizers measure the horizontal polarization or vertical polarization, ‘nonlocal labeling of optical paths’ make the WPI available to the observer. As a result, the entangled single photon does not interfere with itself and a regime favorable to coherent perfect absorption is not established. On the other hand, when one of the eraser states ($|+45\rangle$ or $|-45\rangle$) is

measured at the output of the interferometer, the optical paths become indistinguishable, the single photon interferes with itself, thus a regime favorable to coherent perfect absorption is produced.

In the nonlocal case, instead of post-selecting locally at the interferometer's output, we pre-select by removing the polarizers from the output of the interferometer and effectively add a polarizer in the nonlocal optical path II of the SPDC source. By making use of the nonlocal property of polarization entangled photon pairs, different measurements on the polarization states of the photons in optical path II will enable or disable CPA. This nonlocal effect can be described by devising the following quantum theory.

3.3.6.1 - The Theory

Similarly to the theory for the local quantum eraser CPA, this nonlocal theory is formulated by combining the path entangled wavefunction with the polarization entangled wavefunction in this system. On the other hand, differently from the local case, it is sufficient to describe the experiment with respect to optical paths A and B before the photon reaches the metamaterial. This equivalence is supported by the fact that the nonlocal polarizer in this experiment measures the polarization state of the photons in path II before the photons in path I reach the first beamsplitter BS1 of the quantum eraser interferometer. In other words, a comparable statement to the previous one is that a measurement produced in the nonlocal arm, for instance by setting a polarizer to transmit the horizontal polarization $|H\rangle$, is equivalent to setting the entangled photons in the interferometer before the first beamsplitter BS1 with a polarizer transmitting the vertical polarization $|V\rangle$ only.

It is important to highlight that a nonlocal measurement will **not** affect all the photons in the interferometer. This is due to experimental coupling limitations whereby only 15% of the SPDC photons coupling into the single mode fibers are in a polarization-entangled pure states while the rest of the photons are in mixed states.

Thus, similarly to the theory for the local quantum eraser CPA, we combine both the polarization entanglement and path entanglement wavefunctions displayed below in equations 3.49 and 3.50.

$$|\Psi\rangle = \frac{1}{\sqrt{2}} (|H\rangle_I |V\rangle_{II} - |V\rangle_I |H\rangle_{II}) \quad [3.49]$$

$$|\Psi\rangle = \frac{1}{\sqrt{2}} (|1\rangle_A |0\rangle_B - e^{i\phi} |0\rangle_A |1\rangle_B) \quad [3.50]$$

Further, it follows that for the case of an incident horizontal polarization or vertical polarization we obtain equations 3.51 and 3.52, respectively.

$$|\Psi\rangle = \frac{1}{\sqrt{2}} (|V\rangle_A |0\rangle_B - e^{i\phi} |0\rangle_A |H\rangle_B) \quad [3.51]$$

$$|\Psi\rangle = \frac{1}{\sqrt{2}} (|H\rangle_A |0\rangle_B - e^{i\phi} |0\rangle_A |V\rangle_B) \quad [3.52]$$

We then incorporate them in the polarization entanglement wavefunction (equation 3.49) for each state of the photons from path I, as shown in equation 3.53. Further, it is worth noting that i denotes an added phase for the 90° reflection into path B of the beamsplitter BS1. Similarly to the theory of the local quantum eraser CPA, the wavefunction produced from the expansion of polarization states and zero states depicted in equation 3.54 is rearranged in equation 3.55 to obtain a path entanglement-like form where number state $|1\rangle$ is replaced by polarization entanglement wavefunctions. In addition, we simplify the wavefunctions in the same way as the previous local CPA theory by rendering the relative phase $\Phi = \phi + \pi/2$, since $i = e^{i\pi/2}$.

$$|\Psi\rangle = \frac{1}{2} ((|V\rangle_A |0\rangle_B - ie^{i\phi} |0\rangle_A |H\rangle_B) |V\rangle_{II} - (|H\rangle_A |0\rangle_B - ie^{i\phi} |0\rangle_A |V\rangle_B) |H\rangle_{II}) \quad [3.53]$$

$$|\Psi\rangle = \frac{1}{2} (|V\rangle_A |0\rangle_B |V\rangle_{II} - ie^{i\phi} |0\rangle_A |H\rangle_B |V\rangle_{II} - |H\rangle_A |0\rangle_B |H\rangle_{II} + ie^{i\phi} |0\rangle_A |V\rangle_B |H\rangle_{II}) \quad [3.54]$$

$$|\Psi\rangle = \frac{1}{2} ((|V\rangle_A|V\rangle_{II} - |H\rangle_A|H\rangle_{II})|0\rangle_B - ie^{i\Phi}|0\rangle_A(|H\rangle_B|V\rangle_{II} - |V\rangle_B|H\rangle_{II})) \quad [3.55]$$

Due to the nonlocal property of polarization entangled photons, measuring a horizontal or vertical polarization state in optical path II of the SPDC source projects a state onto photon I, incident on BS1 in the interferometer, and defines its polarization to be vertically or horizontally polarized, respectively. Consequently, under the influence of half-wave plate HWP A, a photon II measured in the horizontal or vertical polarization state will result in creating distinguishability of optical paths in the interferometer. Indeed, as described in equations 3.56 and 3.57, we observe that by measuring the nonlocal entangled photons from path II, the WPI can be obtained. Thus, since distinguishability impairs interference, no coherent perfect absorption regime is produced.

$$\langle H|\Psi\rangle = \frac{1}{2} (-|H\rangle_A|0\rangle_B + e^{i\Phi}|0\rangle_A|V\rangle_B) \quad [3.56]$$

$$\langle V|\Psi\rangle = \frac{1}{2} (|V\rangle_A|0\rangle_B + e^{i\Phi}|0\rangle_A|H\rangle_B) \quad [3.57]$$

Alternatively, in the case of measuring one of the eraser states ($|+45\rangle$) in nonlocal path II represented by equations 3.58 and 3.59, we discern that photons from path I will be collapsed into state $|-45\rangle$. Consequently the WPI will be erased and coherent perfect absorption will occur with the interference of path entangled single photons.

$$\langle +45|\Psi\rangle = \frac{1}{2} \left(\frac{1}{\sqrt{2}} ((|V\rangle_A - |H\rangle_A)|0\rangle_B - e^{i\Phi}|0\rangle_A(|H\rangle_B - |V\rangle_B)) \right) \quad [3.58]$$

$$\langle +45|\Psi\rangle = \frac{1}{2} (|-45\rangle_A|0\rangle_B - e^{i\Phi}|0\rangle_A|-45\rangle_B) \quad [3.59]$$

We furthermore observe that the projection of the $|+45\rangle$ polarization state on the wavefunction in equation 3.59 shares characteristics with the projection for the local quantum eraser CPA in equation 3.37. The difference between these two projections are that the local case displays superpositions of path II and path A or B as opposed to the nonlocal case that displays superpositions of paths A and

B. Indeed, this is due to the fact that path II has already been projected on for the nonlocal case, which is produced experimentally in the next subsection.

3.3.6.2 – The Experiment and the Results

The purpose for conducting this experiment is to show a measurement-dependent nonlocal CPA in the quantum regime with plasmonic metamaterials. As highlighted in the theory previously presented, a measurement is carried out by removing the interferometer's output polarizers and adding a polarizer denoted 'P2' in optical path II of the nonlocal entangled source (see figure 3.20).

Figure 3.20 - Top left: the coincidence counting module receiving single photon counts from single photon detectors. Coincidences are recorded between outputs of interferometer C and D, and the output coupler in path II from the SPDC source.

In this setup, recovering the polarization in the interferometer with the quarter-wave plate QWP and the half-wave plate HWP is particularly important (as described in section 3.3.4). If the polarization is not completely recovered, a nonlocal measurement may project onto a state which is not exactly orthogonal. For instance, setting the polarizer P2 in path II to transmit the horizontal polarization $|H\rangle$ may result in setting the other photons of the entangled pairs in the interferometer to the vertical polarization $|V\rangle$ plus or minus a few degrees. In the case of a nonlocal horizontal polarization measurement, we know from the previously formulated theory that no interference fringes should be detected. Although, if the recovery of the polarization state at the source is not accurate, a few fringes can be detected. As a reminder, a high quality calibration of

polarization at the entrance of the interferometer is produced by virtue of what is defined in this manuscript as a ‘polarization calibration test’ and a ‘Bell measurement calibration test’.

In this experiment, polarizer P2 nonlocally performs a measurement on the polarization state of the photons from path II of the SPDC source. Due to the fact that the measured photons are entangled in a nonlocal manner with the photons from path I, a measurement of the horizontal or vertical polarization on photon II results in photon I being in the vertical or horizontal polarization respectively. In that case, in agreement with the previous statements, no interference fringes will be produced. This is outlined by the fact that the half-wave plate HWP A will induce distinguishability of optical paths by rotating the horizontal and vertical polarizations to their orthogonal polarization states. In this situation, for which the experimental data is presented in figure 3.21(a), coherent perfect absorption will not occur for nonlocal measurements with polarizer P2 on photons in path II in the horizontal and vertical polarizations. Correspondingly, we observe that the measurements in the horizontal polarization state, denoted by green square markers, and the vertical polarization state, denoted by black diamond markers, yield no modulation of absorption as a function of relative phase.

In contrast, denoted in red circles, a nonlocal measurement in the eraser state $|+45\rangle$ produces coherent perfect absorption as a function of relative phase. By measuring the $|+45\rangle$ polarization state of the nonlocal photon in path II with polarizer P2, its entangled photon local to the interferometer originating from path I is projected to the $|-45\rangle$ polarization state and inherently becomes unaffected by the half-wave plate HWP A. On that note, it is important to state that the half-wave plate HWP A with its fast axis forming an angle of $+45^\circ$ or -45° ($=135^\circ$) to the horizontal plane with an incident $|-45\rangle$ polarization state will provide the same output. In one case, the fast axis is forming an angle of -45° ($=135^\circ$) with the horizontal plane and thus is aligned with the incident polarization. Since the rotation of the polarization depends on the difference between the incident polarization and the fast axis, a difference of 0° means that

the polarization will not be rotated and the photon in Path A will remain with a $|-45\rangle$ polarization state. Alternatively, when the fast axis is forming an angle of $+45^\circ$ with the horizontal plane, the incident polarization is not aligned with the fast axis, and instead creates a difference between the incident polarization and the fast axis of $90^\circ (= \pi/2)$. Thus, the polarization will be rotated by twice the difference resulting in $180^\circ (= \pi)$. In this case a $|-45\rangle$ polarization state in the negative horizontal quadrant ($|-45\rangle = \frac{1}{\sqrt{2}} (-|H\rangle + |V\rangle)$) will result in the same polarization but in the negative vertical quadrant ($|-45\rangle = \frac{1}{\sqrt{2}} (|H\rangle - |V\rangle)$). In other words, the polarization will still remain unchanged.

Figure 3.21 - (a) CPA with nonlocal measurements in H (green squares), V (black diamonds) and +45 (red circles). (b) relevance of entanglement with CPA for a high visibility of entanglement and low visibility of entanglement.

In view of investigating the importance of quantum mechanics in this nonlocal effect scheme of coherent perfect absorption, a slight misalignment specific to the position of the coupler for path II was created with the purpose to reduce the quality of quantum entanglement. We define the quality by referring to the visibilities illustrated in figure 2.3. These visibilities are used to calculate the Bell parameter, which in turn validates the quantum optical properties of polarization entangled photon pair sources. Of the two visibilities, the $|\pm 45\rangle$ polarization basis has high importance in drawing the line between quantum sources and classical sources. Its relevance originates from the fact that classical sources with high

visibility in the $|HV\rangle$ polarization basis cannot display high visibility in the $|\pm 45\rangle$ polarization basis.

Figure 3.22 - Visibilities in the crossed-polarization basis for the high entanglement regime used for the experimental results and the low entanglement regime that show a much lower visibility value.

Subsequently, we observe in figure 3.22 two visibility curves for the crossed-polarization basis. The solid line with the red circular markers represents the high visibility entanglement regime with a visibility of 0.859. In contrast, the dotted line with the blue square markers represents the reduced visibility entanglement regime defined by a visibility of 0.559. The Bell parameter for the reduced visibility entanglement regime results in a value of 2.08. By having the Bell parameter being just above 2 this regime is defined as a very poor quantum regime.

Therefore, to conclude this chapter, three different quantum coherent perfect absorption optical schemes were presented. All of them outlined that by way of fabricating asymmetric split-ring arrays on a 50nm freestanding layer of gold, close to full absorption could be achieved through the coherent interference of a single photon. In the first experiment defined in this chapter, we demonstrated that a single photon interfering in its wave-like nature can be absorbed with nearly 100% probability. Furthermore, in the other two experiments, we observe interactions between plasmonic metamaterials and polarization entangled photons. Differently from the previous experiment, we distinguish absorption of

a particle in one case and a wave in the other by virtue of a quantum eraser interferometer. In the local quantum eraser scheme, we place polarizers at the outputs of the interferometer. If we set both polarizers to either the horizontal polarization $|H\rangle$ or the vertical polarization $|V\rangle$, we obtain the absorption of the single photon particle of 50%. On the other hand, by setting both polarizers to either $|+45\rangle$ or $|-45\rangle$, namely the ‘eraser states’, we achieve nearly 100% absorption of the interfering photon wave. More interestingly, the nonlocal quantum eraser scheme is produced by removing the polarizers from the outputs of the interferometer, and placing instead a polarizer in the nonlocal entangled path II of the SPDC source. In this instance, by measuring the photons in path II in the horizontal polarization $|H\rangle$, we project the vertical polarization $|V\rangle$ on the entangled photons local to the interferometer. And similarly for measuring the photons in path II in the vertical polarization $|V\rangle$, we project the horizontal polarization $|H\rangle$ on the entangled photons local to the interferometer. We show that for those measurements we obtain a 50% absorption of the photon particle by reason of setting the polarization that is entering the interferometer for which HWP A in optical path A of the interferometer will create path distinguishability. On the other hand, measuring nonlocally the ‘eraser states’ $|+45\rangle$ or $|-45\rangle$, will project $|-45\rangle$ or $|+45\rangle$ in the interferometer respectively and will not be affected by HWP A. To that end, our results yield a nearly 100% absorption of the photon wave. In other words, in this chapter we explored the **absorptive** properties of interfering heralded and polarization-entangled single photons. In the next chapter, we investigate the **transmission** properties of interfering heralded single photons with nanostructured slits.

Chapter 4

Super-oscillation of a Single Photon

4.1 - Quantum Super-oscillation

In the previous chapter, quantum coherent perfect absorption with sub-wavelength thin metamaterials was defined as an effect that allowed total absorption in the quantum regime. More importantly, this effect only takes place with the interference of the single photon's wave-like nature. In this chapter, we will refer to a modified Young's slit experiment with nanostructures to focus light past the diffraction limit [38], and thus introduce this chapter by underlining a parallel with Jönsson's demonstration of the wave-particle duality of electrons.

As was stated in chapter 1, Claus Jönsson proved that electrons displayed 'wave-particle' duality in the setting of a 'Young's slit' experiment. Due to the short wavelength of electrons, a proper detection scheme required slits of 300 nm in width and 1000 nm in separation. The necessity of fabricating such small slits was concluded after calculating the parameters for a typical optical Young's slit experiment. The Young's slit experiment with light as opposed to electrons requires a slit width of 5cm and a slit separation 20cm. Jönsson states [4] that by

using the optical parameters for his 50kV electrons equivalent to a wavelength of 0.05 Angstroms ($\sim 0.5\text{nm}$) he obtains a resulting distance between the electron source and the slits of 30 km and a resulting distance between the slits and the observation plane of 40km.

Jönsson first fabricated two Young's slit masks, a mask of a single slit and a mask of two slits depicted on the left hand side in figure 4.1(a) and 4.1(b) respectively. He then ran the experiment and subsequently imaged the diffraction pattern from a fluorescent screen with a camera and observed the results displayed in figure 4.1(a),(b) on the right hand side.

Figure 4.1 - (a) Young's one slit experiment, (b) Young's two slit experiment, (c) Young's three slit experiment, (d) Young's four slit experiment, (e) Young's five slit experiment. (a) – (d) have the electron micrograph images of the structures on the left and the camera image of the diffraction patterns on the right.

In view of understanding the progression of the diffraction pattern in Young's N-slit experiment, he then fabricated and recorded the diffraction patterns for $N = 3, 4$, and 5 . What he noticed is that the diffraction patterns due to constructive interference were multiplying as a function of N . As an extension to a Young's N-slit experiment, one may be curious on the result of having N-slits with varying slit-widths and separations. Incidentally, this question is answered from our experimental data in this chapter with heralded single photons for the purpose of focusing quantum states of light under the effect of a super-oscillatory lens.

In 1952, Torraldo diFrancia suggested to use principles of super-directive antennas to focus light past the diffraction limit [39]. Super-directive antennas, as depicted below in figure 4.2 on the left, were first adopted to the radiowave frequency regime. As a result of collective interference effects, signals are constructively interfering into one particular high intensity spot denoted as the ‘super-directive beam’.

Figure 4.2 - Similarities between super-directive antennas illustrated on the left and super-oscillatory lenses, illustrated on the right.

Optical Super-oscillations were an inspiration of super-directive antennas as a method to focus light to a spatially confined spot. [40, 41, 42, 43, 44, 45, 46]. They can be generated with metamaterials of organized [47] or random nanostructures [48, 49] by tailoring interferences of propagating electromagnetic waves for which the resulting waveform contains variations faster than the highest spatial frequency component [50]. By doing so, a portion of the incident light can be concentrated in a spot that goes beyond the Abbe diffraction limit, defined by equation 4.1. The equation for the Abbe diffraction limit establishes that the limitation in resolution d of an optical microscope is dependent on the wavelength λ and the numerical aperture NA .

$$d = \frac{1.22\lambda}{2NA} \quad [4.1]$$

In view of the fact that superoscillation optical waves have been shown theoretically to have the potential of forming arbitrarily small spatial localizations [51], this type of super-resolution technique has attracted attention for applications in microscopy on the nanometer scale.

That said, super-oscillation displays an inconvenient feature as shown in figure 4.3. As a result of localizing part of the light to a small area, a portion of the energy from the incident wave will not appear in the ‘hot spot’ but instead in the ‘sidebands’. As shown below the sideband intensity is greater than that of the hotspot intensity, which means that for microscopy, they would excite a material just as much as the hotspot would, resulting in noise.

Figure 4.3 - Labeled graph showing the field of view, the hotspot width and sideband.

In fact, the sideband characteristics are used to qualitatively describe super-oscillation masks, namely super-oscillation lenses (SOLs). The ratio of the ‘peak hot-spot intensity’ to the ‘grass level’ intensity defines the quality of fabrication of the SOL. This particular ratio may also be influenced by the noise level of the imaging devices used. In addition, the ratio of the hotspot intensity to the sidebands intensity defines the efficiency with which the SOL confines light to a small spot.

My role in the work presented in this chapter was to build the optical apparatus and conduct the quantum optical measurements. In the next sub-chapters, we

provide a short introduction on the concept behind this project before expanding on the details of the experiment and finally discussing the results.

4.2 - The Concept

Figure 4.4 - (a) Interference fringes for a Young two-slit experiment. (b), tailored interference of super-oscillatory lens.

As previously stated, the smallest size of a focal spot created by a lens is limited by the Abbe diffraction-limit. With respect to this lower bound, super-oscillation lenses present an interesting opportunity due to their proven ability to confine classical light past the diffraction limit through carefully tailored interferences [52]. Thus, with regards to the interference of quantum states of light, the motivation for this work is best defined as the functionalization of interferences of single photons as a wave in the interest of focusing light past the diffraction limit. In this case, a single photon is said to be path-entangled as a result of being in superposition of ‘slit’ optical paths. The difference with the standard Young’s slit experiment illustrated in figure 4.4 originates from the fact that instead of being entangled in 2 optical paths, the single photon is path-entangled in 48 optical paths for which the slit sizes vary from 200nm to 400nm.

Figure 4.5 - SEM image of the fabricated meta-lens, and definition of $|H\rangle$ and $|V\rangle$ polarizations.

The functioning SOL (imaged with an SEM) in figure 4.5 was fabricated on a thermally evaporated 100nm thick layer of gold and the slits were milled at a current of 24pA with an FIB. The parameters were optimized and the lens was fabricated by my colleague Dr. Guanghui Yuan.

4.3 - The Experiment

Figure 4.6 - Illustration of the optical setup for the $g^{(2)}(0)$ measurement.

Due to the fact that our experiment highly depends on the single photon ‘wave-particle’ behavior, a $g^{(2)}(0)$ measurement was conducted with the help of Dr.

Stefano Vezzoli. The measurement yielded a ‘dip’ value of 0.088 ± 0.029 . By reason of obtaining a value defined to be much less than 0.5 for our $g^{(2)}(0)$ measurement, we can safely confirm that our source generates single photons. These results were produced with the optical setup illustrated in figure 4.6 whereby an SPDC in a 2mm BBO crystal generates two optical paths corresponding to the two photons of the pairs. One photon goes to the coupler denoted N_g , while the other photon goes through a 50:50 beamsplitter and couples into two different outputs, namely N_1 and N_2 .

Figure 4.7- Optical setup for the superoscillation of a single photon experiment. The SPDC source to the right generates single photon pairs at the BBO crystal. One of the photons of the pair is counted in coincidence via a single photon counter. The other photon is transmitted through the sample and ends up being collected at the ‘collection SMF’.

Once the single photon regime was validated, the experimental apparatus was then produced for the SOLs. As illustrated in figure 4.7, the heralded single photon pairs were coupled into two different single mode fibers. One of the photons was guided through the fiber to a single photon detector for which each count was registered in the coincidence counting module. Meanwhile, the other photon experienced super-oscillation by transmitting through the sample. In order to optimize the coupling regime, a 150x objective collimated light out of the SOL. By flipping down the flip mirror, denoted in the figure as ‘Flipping

Mirror', 'Mirror 2' reflected the transmitted photons. With the SOL mounted with slits along the horizontal direction, the 'Cylindrical lens' converted the transmitted two-dimensional horizontal bands into a one-dimensional vertical array of points. In view of measuring every point, a single mode fiber coupler mounted on a motorized stage performed a vertical scan. In the interest of finding the correct focal distance of the SOL, the vertical scan was produced for different positions of the objective with a nanometer resolution provided by a piezoelectric stage.

The optical alignment was conducted with a low intensity 808nm continuous wave alignment laser. We centered the sample by using a conventional CCD camera and by virtue of reflecting the 'white light illumination' source on the 'Beamsplitter' and flipping up the 'Flipping mirror', the nanostructures were imaged in transmission. It should be noted that the 'Beamsplitter' was necessary to illuminate the sample in reflection and to transmit the alignment beam of 70 μ m in diameter.

Moreover, since different SOLs were fabricated on the same film, all of them needed to be measured to qualitatively compare them with each other. In order to align with a neighboring nanostructured SOL, a wider view of the sample was required. We accomplished this task by placing a lens at the larger end of the objective. Consequently, as illustrated in figure 4.8a, a minor focus on the transmitted light allowed the imaging of all the nanostructures. We can also discern a circular hole on the right of the two horizontally aligned SOLs. That feature was needed to image the spot on the surface of the sample in order to optimize the focus within the optical setup.

Figure 4.8 - (a) Imaging the map of all structures to align different structures, (b) imaging of a single SOL, (c) imaging of the hotspot and sidebands.

With a proper alignment, the lens was then removed from behind the objective in order to magnify the single SOL as illustrated in figure 4.8b. Furthermore, we observed that due to diffraction, the change in position of the objective produced a change in the intensity of the light transmitted through the horizontal bands. Thus, when the objective is positioned at the focal point depicted in figure 4.8c, the high intensity center band hotspot is visible with the two symmetrical sidebands at the top and the bottom of the image.

4.4 - The Results

Following an in-depth alignment optimization by centering all the optics with the signal (especially the x150 objective) and exploring different collimation regimes, measurements were conducted for both the horizontal and vertical polarizations denoted in figure 4.9 as $|H\rangle$ and $|V\rangle$ respectively. For each polarization, the SOL generated hot spots observed at the focal length of 10 μm .

Figure 4.9- Super-oscillatory hotspot of a single photon for (a) the horizontal polarization $|H\rangle$ and (b) the vertical polarization $|V\rangle$.

By analyzing our results depicted in the above figure, two SOL profiles are presented. Each profile constitutes of SOL measurements of: 1) the 808nm continuous wave alignment beam (in red), and 2) the SPDC heralded single photon source calculated error bars (in blue). In addition, 3) a calculated diffraction-limited profile is provided (in black). The profile on the left represents the measurement produced with the horizontal polarization $|H\rangle$ and on the right for the vertical polarization $|V\rangle$. In order to produce these two polarizations, HWP2 portrayed in figure 4.7 was geometrically rotated. We notice that the single photon and classical FWHMs are inferior to the diffraction-limited FWHM for both polarizations. In fact, for the single photon source, the calculated FWHM for the horizontal polarization $|H\rangle$ is $(0.49 \pm 0.02)\lambda$, and for the vertical polarization $|V\rangle$ is $(0.48 \pm 0.03)\lambda$. Thus, our hot spots qualify as being smaller than the conventional diffraction limit : $\lambda/(2NA_{\text{SOL}}) = 0.53 \lambda$ for $NA_{\text{SOL}} = 0.949$.

In addition, figure 4.10 compares the analytical calculations and the FDTD simulations with the classical measurements. It shows an increase in noise unique to the experiment and the different profiles for the horizontal and vertical polarizations emphasized for the analytical calculations.

Figure 4.10 - Comparison of analytical calculations, FDTD simulations and the classical measurement for the horizontal polarization and vertical polarization.

Thus, this experiment provided an insight on a Young's N-slit experiment by using the wave-particle duality feature of single photons in the generation of super-oscillatory hot spots. The results have confirmed that both the classical and quantum profiles can generate approximately the same hot spot size. If SOLs are used classically for super-resolution imaging, perhaps this first experiment in quantum super-oscillation creates an opportunity for using path-entangled single photons to focus quantum states of light.

Chapter 5

Conclusions and Recommendations

5.1 - The Conclusion

The work produced in this thesis was motivated by the importance of studying the influence of nanostructured metamaterials on quantum states of light in the context of quantum interferences provided by the ‘wave-particle’ duality of a single photon. Furthermore, the results demonstrate that the absorptive material properties proven useful for classical waves, also applies to the quantum regime. Moreover, our findings present the novelty of focusing a single photon through its wave-like nature with metamaterials. These points have been highlighted through the descriptions of:

- The first demonstration of coherent perfect absorption with a heralded photon source. The results showed that by fabricating a 50% absorbing metamaterial, a single photon can be absorbed with nearly 100% probability.
- A demonstration of the nonlocal property of coherent perfect absorption with polarization entangled photon pairs. The results draws a parallel between the ‘wave-particle’ duality in a Sagnac interferometer in an absorption scheme, whereby a single photon particle get absorbed with only 50% probability as opposed to a single photon wave absorbed with near 100% probability. In addition, we underline the difference in

visibility of ‘nonlocal’ modulation of absorption between a strong and a weak quantum regime.

- The construction of a ‘post-selective’ quantum eraser in controlling ‘locally’ the coherent perfect absorption regime.
- The first fabrication of a polarization-independent asymmetric split-ring nanostructured plasmonic metamaterial for superposition of orthogonal states.
- The validation of a Young’s N-slit experiment in super-oscillating a single photon wave for the purpose to focus quantum states of light past the Abbe diffraction limit.

By establishing and defining techniques in the study of interactions between nanostructured metamaterials and quantum states of light, the results produced contribute to finding new applications specific to the use of material properties for operating on the quantum state of path-entangled and polarization-entangled single photons.

5.2 - Recommendations for Further Research

5.2.1 - EPR States Nonlocal Measurements with Plasmonic Slits

Further research could be conducted in the investigation of nonlocal coherent perfect absorption with a nonlocal two-plasmon interference. In this instance, I refer to the experiment by Pysher *et al.* for which the principle was first demonstrated by Franson [53]. A polarizer is placed at each outputs of the interferometer and in the nonlocal arm. The difference in this proposed experiment is that here the measurements on the polarization are done with nanostructured plasmonic slits and similarly to Pysher *et al.*’s experiment the nonlocal fringes are produced with a Pancharatnam-Berry phase shifter denoted (PBPS).

Figure 5.1 - Proposed optical setup where one of the photons of the pairs (left) goes to the CPA interferometer while the other photon of the pairs (right) is measured with the plasmonic slit nanostructure.

The slits displayed below in figure 5.2 were fabricated by using an FIB for the purpose of absorbing a very specific polarization. The gold layer thermally evaporated on glass is 100nm thick. The orthogonal polarization (to the slit orientation) is the vertical polarization, and transmits 8.5%, and the polarization parallel to the slits, thus the horizontal polarization, transmits 0.2%. In that event, a transmitted idler photon will produce a coincidence count with the signal photon of the nonlocal path of the source and in the case of a horizontal-vertical Bell measurement, the visibility should be relatively high.

Figure 5.2 - On the right, the SEM image of the plasmonic slits. On the left, the Bell measurement in the horizontal-vertical polarization basis.

Indeed, a Bell measurement was produced on the polarization entangled photons by rotating a half-wave plate in front of a polarizing beamsplitter (equivalent to a polarizer) at the source. Further, a nonlocal transmission arm was built and aligned with the metamaterial by imaging with a CCD camera in reflection.

Figure 5.3 - Bell measurement with plasmonic slits in the horizontal-vertical polarization basis.

In the above figure 5.3, we observe that the normalized coincidence counts come close to zero. When the plasmonic slit visibility was calculated it yielded a value of 90% as opposed to a polarizer visibility of 92%. Hence, if a nonlocal two photon interference is produced with the fabricated horizontal slit array, nonlocal interference fringes under the regime CPA should appear.

5.2.2 - CPA for Polarization Rotation

For the purpose of functionalizing the CPA optical scheme, an interesting idea was suggested by Kang M. and Chong Y.D. [54]. In their theoretical formulation, a metamaterial with particular parameters is placed in an interferometric CPA-like optical apparatus. By changing the relative phase of the optical paths, the linear polarization of the incident beams is rotated at the outputs. In other words, this concept portrays a CPA half-wave plate.

In this suggestion for further research I will show results of our attempt of conducting this experiment and highlight the reasons why we were not able to complete it. Hence, I point to the specific issues we were faced with.

In planning to conduct this experiment, particular attention was focused on the metamaterial's parameters. One parameter called 'g' for 'gap' seemed to be the indicator of rather or not our experiment was going to yield successful results. We observe from figure 5.4(c) below, that 'g' represents the gap between the two metallic structures. More specifically, the design is made of two components: a 'C' shaped component on the top and below a horizontal 'I' shaped component. In the theory, these are made of silver and the rest of the dashed square is air. Moreover, we notice in figure 5.4(d) that the quality of the coupling and conversion of the polarization depends on the value of the gap 'g'.

Figure 5.4 - (a) Resonance in reflection as a function of an incident x polarization. **(b)** Resonance in reflection as a function of an incident y polarization. **(c)** parameters of the unit cell of the silver metamaterial array. **(d)** dependence of the coupling regime on the gap.

Indeed, even when we converted the simulation to the necessary opposite structure which was comprised of the components being made of air, and the rest of the square made of silver, the importance of ‘g’ as a quality did not change. Hence, a gap of 20nm needed to be fabricated.

With the help of our collaborator (Dr. Joao Valente) we attempted to fabricate this particular metamaterial. We see below illustrated in figure 5.5(c) the closeup of the unit cells of the best array. We can observe that the ‘I’ shaped horizontal feature is not always milled from end to end, and that indeed was translated through the reflection and transmission spectrum.

Figure 5.5 - SEM images: (a) Metamaterial membrane with the array centered, (b) overview of a part of the array, (c) closeup of the unit cells.

Due to the fact that the images above represent a highly optimized fabrication, and that the interferometer is already aligned, it suggests that in order to conduct this experiment, the only difficulty is fabrication related.

Appendix

Intensity (%)

Wavelength (nm)

500

800

1100

1400

0

50

100

Intensity (%)

Wavelength (nm)

500

800

1100

1400

0

50

100

Intensity (%)

Wavelength (nm)

500

800

1100

1400

0

50

100

SR5

FIB settings

Center-to-center distance &
Line spacing: 8.47 nm
Current dose: 6.40 nC/cm

	H	V	45°
Reflection	~25%	~26%	~24%
Transmission	~29%	~29%	~30%
Absorption	~45%	~45%	~46%

R

T

A

Horizontal Polarization

Vertical Polarization

+45 Polarization

Intensity (%)

Wavelength (nm)

500

800

1100

1400

0

50

100

Intensity (%)

Wavelength (nm)

500

800

1100

1400

0

50

100

Intensity (%)

Wavelength (nm)

500

800

1100

1400

0

50

100

SR6

FIB settings

Center-to-center distance &
Line spacing: 8.47 nm
Current dose: 6.10 nC/cm

	H	V	45°
Reflection	~43%	~35%	~41%
Transmission	~16%	~21%	~17%
Absorption	~41%	~44%	~42%

SR7

FIB settings

Center-to-center distance &
Line spacing: 7.06 nm
Current dose: 6.10 nC/cm

	H	V	45°
Reflection	~44%	~35%	~44%
Transmission	~14%	~21%	~16%
Absorption	~42%	~44%	~40%

Horizontal Polarization

Vertical Polarization

+45 Polarization

SR8

FIB settings

Center-to-center distance &
Line spacing: 7.06 nm
Current dose: 6.70 nC/cm

	H	V	45°
Reflection	~46%	~28%	~43%
Transmission	~14%	~27%	~18%
Absorption	~40%	~45%	~39%

Horizontal Polarization

Vertical Polarization

+45 Polarization

Bibliography

- [1] Taylor, G. I. Interference fringes with feeble light. *Proc. Camb. Philos. Soc.*, **15**, 114-115 (1909).
- [2] Aspect, A. and Grangier, P. Wave-particle duality for single photons. *Hyp. Inter.* **37**, 3-18 (1987).
- [3] Davisson, C., and Germer, L.H. Reflection of electrons by a crystal of nickel. *Nature* **119**, 558-560 (1927).
- [4] Jönsson, C. Zeitschrift für Physik 161 (1961), 454. Reprinted in English as "Electron diffraction at multiple slits," *Am. J. Phys.* **42**, 4-11 (1974).
- [5] Zheludev, N. I., and Kivshar, Y. S. From metamaterials to metadevices. *Nat. Mat.* **11**, 917-924 (2012).
- [6] Zheludev, N. I. A roadmap to metamaterials. *OPN* **22**, 30-35 (2011).
- [7] Barnes, W. L., Dereux, A., Ebbesen, T. W. Surface plasmon subwavelength optics. *Nat.* **424**, 824-830 (2003).
- [8] Ebbesen, T. W., Lezec, H. J., Ghaemi, H. F., Thio, T., Wolff, P. A. Extraordinary optical transmission through sub-wavelength hole arrays. *Nature*, **391**, 667-669 (1998).
- [9] Schouten, H.F., Kuzmin, N., Dubois, G., Visser, T.D., Gbur, G., Alkemade, P.F.A., Blok, H., 't Hooft, G.W., Lenstra, D. and Eliel, E.R., "Plasmon-assisted two-slit transmission: Young's experiment revisited," *Phys. Rev. Lett.*, **94**, 053901 (2005).

-
- [10] Altewischer, E., van Exter, M. P., Woerdman, J. P. Plasmon-assisted transmission of entangled photons. *Nature* **418**, 304-306 (2002).
- [11] Kolesov, R., Grotz, B., Balasubramanian, G., Stöhr, R. J., Nicolet, A. A. L., Hemmer, P. R., Jelezko, F., Wrachtrup, J. Wave-particle duality of single surface plasmon polaritons. *Nat. phys.* **5**, 470-474 (2009).
- [12] Dheur, M-C., Devaux, E., Ebbesen, T. W., Baron, A., Rodier, J-C., Hugonin, J-P., Lalanne, P., Greffet, J-J., Messin, G., Marquier, F. Single-plasmon interferences. *Sci. Adv.* **2**:e1501574 (2016).
- [13] Brouri, R., Beveratos, A., Poizat, J-P., Grangier, P. Photon antibunching in the fluorescence of individual color centers in diamond. *Opt. Lett.* **25**, 1294 (2000).
- [14] Michler, P., Kiraz, A., Becher, C., Schoenfeld, W. V., Petroff, P. M., Zhang, L., Hu, E., Imamoglu, A. A quantum dot single-photon turnstile device. *Science* **290**, 2282-2285 (2000).
- [15] Santori, C., Pelton, M., Solomon, G., Dale, Y., Yamamoto, Y. Triggered single photons from a quantum dot. *Phys. Rev. Lett.* **86**, 1502 (2001).
- [16] Clauser, J. F. Experimental distinction between the quantum and classical field-theoretic predictions for the photoelectric effect. *Phys. Rev. D.* **9**, 853 (1974).
- [17] Einstein, A., Podolsky, B., Rosen, N. Can quantum-mechanical description of physical reality be considered complete? *Phys. Rev.* **47**, 777 (1935).
- [18] Aspect, A., Grangier, P., Roger, G. Experimental realization of Einstein-Podolsky-Rosen-Bohm Gedankenexperiment: A new violation of Bell's Inequalities. *Phys. Rev. Lett.* **49**, 2 (1982).

-
- [19] Kiess, T. E., Shih, Y. H., Sergienko, A. V., Alley, C. O. Einstein-Podolsky-Rosen-Bohm experiment using pairs of light quanta produced by type-II parametric down-conversion. *Phys. Rev. Lett.*, **71**, 24 (1993).
- [20] Kwiat, P. G., Mattle, K., Weinfurter, H., Zeilinger, A., Sergienko, A. V., Shih, Y. New High-intensity source of entangled-photon pairs. *Phys. Rev. Lett.* **75**, 24 (1995).
- [21] Clauser, J. F., Horne, M. A., Shimony, A., Holt, R. A. Proposed experiment to test local hidden-variable theories. *Phys. Rev. Lett.* **23**, 880 (1969).
- [22] Poh, H. S., Joshi, S. K., Cerè, A., Cabello, A., Kurtsiefer, C. Approaching Tsirelson's Bound in a Photon Pair Experiment. *Phys. Rev. Lett.*, **115**, 180408 (2015).
- [23] Kurtsiefer, C., Oberparleiter, M., Weinfurter, H. High-efficiency Entangled Photon Pair Collection in Type-II Parametric Fluorescence. *Phys. Rev. A.*, **64**, 023802 (2001).
- [24] McPeak, K. M., Jayanti, S. V., Kress, S. J. P., Meyer, S., Iotti, S., Rossinelli, A., Norris, D. J. Plasmonic Films Can Easily Be Better: Rules and Recipes. *ACS Photon.* **2**(3) (2015).
- [25] Chong, Y. D., Li Ge, Hui Cao, and A. D. Stone. Coherent Perfect Absorbers: Time Reversed Lasers. *Phys. Rev. Lett.* **105**, 053901 (2010).
- [26] Wan, Chong, Y. D., Li Ge, Noh, A. D. Stone, Hui Cao. Time-reversed Lasing and Interferometric Control of Absorption. *Science* **331**, 889-892 (2011).
- [27] Zhang, J., MacDonald, K. F., Zheludev, N. I. Controlling light-with-light without nonlinearity. *Light: Sci. Appl.* **1**, e18 (2012).
- [28] Huang, S., Agarwal, G.S. Coherent Perfect Absorption of Path Entangled Single Photons. *Opt. Exp.* **22**, 20936 (2014).

[29] Dirac, P. A. M. The Principles of Quantum Mechanics, Fourth Edition. *Oxford University Press*, pg. 8-11 (1958).

[30] Scully, M. O., Drühl, K. Quantum eraser: A proposed photon correlation experiment concerning observation and “delayed choice” in quantum mechanics. *Phys. Rev. A*, **25**, 4 (1982).

[31] Scully, M. O., Englert, B-G., Walther, H. Quantum Optical Tests of Complementarity. *Nat.* **351**, 311-317 (1991).

[32] Scully, M. O., Kim Y-H., Yu, R., Kulik, S. P., Shih, Y. Delayed “choice” quantum eraser. *Phys. Rev. Lett.* **84**, 1 (2000).

[33] Pysher, M. J., Galvez, E. J., Misra, K., Wilson, K. R., Melius, B. C., Malik, M. Nonlocal labeling of paths in a single photon interferometer. *Phys. Rev. A*, **72**, 052327 (2005).

[34] Haldane, F. D. M. Path dependence of the geometric rotation of polarization in optical fibers. *Opt. Lett.* **11**, 11 (1986).

[35] Tomita, A., Chiao, R. Y. Observation of Berry’s topological phase by use of an optical fiber. *Phys. Rev. Lett.*, **57**, 8 (1986).

[36] Zel’dovich, B. Y., Kundikova, N. D. Intrafibre rotation of the plane of polarization. *Q.Electron.*, **25**, 2 (1995).

[37] Roger, T., Vezzoli, V., Bolduc, E., Valente, J., Heitz, J. J. F., Jeffers, J., Soci, C., Leach, J., Couteau, C., Zheludev, N. I., Faccio, D. Coherent perfect absorption in deeply subwavelength films in the single photon regime. *Nat. Commun.* **6**:7031 (2015).

[38] Dorn, R., Quabis, S., Leuchs, G. Sharper focus for a radially polarized light beam. *Phys. Rev. Lett.*, **91**, 233901 (2003).

-
- [39] di Francia, T. Super-gain antennas and optical resolving power. *Nuovo Cimento suppl.* **9**, 426-435 (1952).
- [40] Zheludev, N. I. What diffraction limit? *Nat. Mater.* **7**, 420-422 (2008).
- [41] Woodward B. P. M. and Lawson J. D. The theoretical precision with which an arbitrary radiation-pattern may be obtained from a source of finite size. *J. Inst. Electr. Eng.* III. **95**, 363–370 (1948).
- [42] Schelkunoff, S. A. A mathematical theory of linear arrays. *Bell Syst. Tech. J.* **22**, 80–107 (1943).
- [43] Bouwkamp, C. J. and De Bruin N. G. The problem of optimal antenna current distribution. *Phillips Res. Rep.* **1**, 135–158 (1945).
- [44] Wong, A. M. H. and Eleftheriades, G. V. Adaptation of Schelkunoff's superdirective antenna theory for the realization of superoscillatory antenna arrays *IEEE Antennas Wirel. Propag. Lett.* **9**, 315–318 (2010).
- [45] Wong, A. M. H. and Eleftheriades, G. V. Sub-wavelength focusing at the multi-wavelength range using superoscillations: an experimental demonstration *IEEE Trans. Antennas Propag.* **59**, 4766–4776 (2011).
- [46] Bucklew, J. A. and Saleh, B. E. A. Theorem for high-resolution high-contrast image synthesis *J. Opt. Soc. Am. A* **2**, 1233 (1985).
- [47] Roy, T., Rogers, E. T. F. and Zheludev, N. I. Sub-wavelength focusing meta-lens *Opt. Exp.* **21**, 7577 (2013).
- [48] Berry, M. V. and Dennis, M. R. Natural superoscillations in monochromatic waves in D dimensions. *J. Phys. A: Math. Theor.* **42**, 022003 (2009).

- [49] Dennis, M. R., Hamilton, A. C. and Courtial, J. Superoscillation in speckle patterns *Opt. Lett.* **33**, 2976–2978 (2008).
- [50] Rogers, E. T. F., Zheludev, N. I. Optical super-oscillations: sub-wavelength light focusing and super-resolution imaging. *J. opt.* **15**, 094008 (2013).
- [51] Berry, M. V. and Popescu, S. Evolution of quantum superoscillations and optical superresolution without evanescent waves. *J. Phys. A: Math. Gen.* **39**, 6965–6977 (2006).
- [52] Zheludev, N. I. What diffraction limit? *Nat. Mater.* **7**, 420-422 (2008).
- [53] Franson, J. D. Bell inequality for position and time. *Phys. Rev. Lett.* **62**, 19 (1989).
- [54] Kang, M. and Chong Y. D. Coherent optical control of polarization with a critical metasurface. *Phys. Rev. A.* **92**, 043826 (2015).

Author's Publications

Journal Publications

Yuan, G. H., Vezzoli, S., Altuzarra, C., Rogers, E. T. F., Couteau, C., Soci, C., Zheludev, N. I. Quantum super-oscillation of a single photon. *Light: Sci. & Appl.* **5**, e16127 (2015).

Submitted:

Altuzarra, C., Vezzoli, S., Valente, J., Gao, W., Soci, C., Faccio, D., Couteau, C., Zheludev, N. I. Nonlocal control of dissipation with entangled photons.

Conference Contributions

(Poster) ““Remote control” of coherent light absorption with entangled photons”.

C. Altuzarra, S. Vezzoli, J. Valente, C. Soci, D. Faccio, C. Couteau, N. I. Zheludev.

CLEO 2016, San Jose Convention Center, San Jose, CA, USA, 5 - 10 June 2016

(Invited) “Image recognition and quantum gating with plasmonic metadevices”
- N. I. Zheludev, M. Papaioannou, C. M. X. Altuzarra, S. Vezzoli, J. Valente, C. Couteau, E. Plum, K. F. MacDonald, C. Soci, and D. Faccio, SPIE Optics & Photonics 2016, San Diego, USA, 28 Aug - 1 Sep 2016.

(Poster) “Metamaterial coherent plasmonic absorption with a single photon”.

C. Altuzarra, S. Vezzoli, J. Valente, J. Heitz, J. Jeffers, J. Leach, C. Couteau, C. Soci, N. I. Zheludev, D. Faccio.

Japan-Singapore International Workshop on Nanophotonics, Plasmonics, and Materials, Singapore, December 11-14, 2014.

(Poster) “Superoscillation of a single photon”.

G. Yuan, S. Vezzoli, C. Altuzarra, E. Rogers, C. Couteau, C. Soci, Z. Shen, N. I. Zheludev.

The 5th International Topical Meeting on Nanophotonics and Metamaterials (NanoMeta 2015), Seefeld, Austria, January 5-8, 2015.

(Oral) “Metamaterial coherent plasmonic absorption with a single photon”. C.

Altuzarra, S. Vezzoli, T. Roger, E. Bolduc, J. Valente, J. Heitz, J. Jeffers, J. Leach, C. Couteau, C. Soci, N. I. Zheludev, D. Faccio. The 5th International Topical Meeting on Nanophotonics and Metamaterials (NanoMeta 2015), Seefeld, Austria, January 5-8, 2015.

(Poster) “Metamaterial absorption with quantum states of light”.

C. Altuzarra, S. Vezzoli, J. Valente, W. Gao, C. Soci, D. Faccio, C. Couteau, N. I. Zheludev.

“Complex Photonics”, International School of Physics Enrico Fermi, July 2015.

(Oral) “Remote Control of Perfect Absorption in Plasmonic Material with Entangled Photons”.

C. Altuzarra, S. Vezzoli, J. Valente, W. Gao, C. Soci, D. Faccio, C. Couteau, N. I. Zheludev.

META Conference, New York, August 2015.

(Oral-Awarded) ““Remote control” of perfect absorption in plasmonic metamaterial with entangled photons”.

C. Altuzarra, S. Vezzoli, J. Valente, W. Gao, C. Soci, D. Faccio, C. Couteau, N. I. Zheludev.

SPIE, Asian CORE student Meeting, December 8-9, 2015.

(Poster-Awarded) ““Remote control” of perfect absorption in plasmonic metamaterial with entangled photons”

C. Altuzarra, S. Vezzoli, J. Valente, W. Gao, C. Soci, D. Faccio, C. Couteau, N. I. Zheludev.

Nanophotonics in Asia 2015, December 10-11, 2015.

(Poster) ““Remote control” of absorption in a metamaterial with entangled photons”.

C. Altuzarra, S. Vezzoli, J. Valente, W. Gao, C. Soci, D. Faccio, C. Couteau, N. I. Zheludev.

The Abdus Salam International Centre for Theoretical Physics – Quantum Information Processing, January 18-29, 2016.