Optically tailored magnetic potentials for ultracold atoms based on superconducting vortices

Phyo, Baw Swe

2019

Phyo, B. S. (2019). Optically tailored magnetic potentials for ultracold atoms based on superconducting vortices. Doctoral thesis, Nanyang Technological University, Singapore.

<https://hdl.handle.net/10356/90331>

<https://doi.org/10.32657/10220/49904>

**NANYANG
TECHNOLOGICAL
UNIVERSITY**

SINGAPORE

**OPTICALLY TAILORED MAGNETIC
POTENTIALS FOR ULTRACOLD ATOMS BASED
ON SUPERCONDUCTING VORTICES**

PHYO BAW SWE

**SCHOOL PHYSICAL AND MATHEMATICAL
SCIENCES**

2019

**OPTICALLY TAILORED MAGNETIC
POTENTIALS FOR ULTRACOLD ATOMS BASED
ON SUPERCONDUCTING VORTICES**

PHYO BAW SWE

**SCHOOL PHYSICAL AND MATHEMATICAL
SCIENCES**

**A thesis submitted to the Nanyang Technological University
in partial fulfilment of the requirement for the degree of
Doctor of Philosophy**

2019

Statement of Originality

I hereby certify that the work embodied in this thesis is the result of original research, is free of plagiarised materials, and has not been submitted for a higher degree to any other University or Institution.

09/09/2019

.....
09/09/2019

Phyo

.....
Phyo Baw Swe

Supervisor Declaration Statement

I have reviewed the content and presentation style of this thesis and declare it is free of plagiarism and of sufficient grammatical clarity to be examined. To the best of my knowledge, the research and writing are those of the candidate except as acknowledged in the Author Attribution Statement. I confirm that the investigations were conducted in accord with the ethics policies and integrity standards of Nanyang Technological University and that the research data are presented honestly and without prejudice.

09/09/2019

.....
09/09/2019

.....
Prof. Rainer Helmut Dumke

Authorship Attribution Statement

This thesis contains material from a paper published in the following peer-reviewed journal in which I am listed as an author.

Chapter 4 and 5 are published as Francesca Tosto, Phyo Baw Swe, Nghia Tin Nguyen, Christoph Hufnagel, María Martínez Valado, Leonid Prigozhin, Vladimir Sokolovsky and Rainer Dumke. Optically tailored trapping geometries for ultracold atoms on a type-II superconducting chip. Appl. Phys. Lett. 114, 222601 (2019); <https://doi.org/10.1063/1.5096997>.

The contributions of the co-authors are as follows:

- Associate Prof. Rainer provided the initial project direction and edited the manuscript drafts.
- I and my project partner, Francesca, prepared the manuscript drafts. The manuscript was revised by Dr. Christoph.
- I co-designed the study with Prof. Rainer and performed all the laboratory work at the School of Physical and Mathematical.
- All data acquisition, analysis and characterization were conducted by me and my project partner, Francesca.
- Dr. Maria and Tin Nguyen assisted in setting up the experiment.
- Prof. Leonid Prigozhin and Prof. Vladimir Sokolovsky assisted in simulation of magnetic field distributions.

09/09/2019

.....
09/09/2019

.....
Phyo Baw Swe

Abstract

Atom chips are micro-fabricated devices which create versatile magnetic potentials for trapping, cooling and controlling ensembles of ultra-cold atoms. Advancing from the typical atom chips, currents from superconducting vortices are used to trap and manipulate the ultra-cold atoms in our experiments. The superconducting vortex traps can be configured by controlling strength and pulse time of external magnetic fields together with bias fields. In order to fully utilize reconfigurability, superconducting vortices are optically manipulated with laser light to generate desired vortex patterns with this tailored trapping potentials for ultra-cold atoms are created. We have carried out heat diffusion simulations of laser patterns and characterized laser power and pulse time to effectively configure the desired vortex potentials. We have also successfully manipulated vortex matter optically to create arbitrary vortex patterns and ring potentials for cold atoms to utilize in quantum simulations and on-chip matter wave interferometry applications. Moreover, cold atoms could be used as a sensitive probe to examine magnetic field distribution of the superconducting vortices and we have used this technique to experimentally verify the resulting magnetic potentials of superconducting vortices after optical manipulation.

Acknowledgements

First of all, I would like to express my heartfelt gratitude and appreciation to my teacher and mentor, Prof. Rainer Dumke for continuous guidance and encouragement throughout my Ph.D. I could not ask for a better advisor for my Ph.D. study. I am also grateful for my thesis advisory committee: Prof. Tomasz Paterek, Prof. Claus Dieter Ohl, and Prof. Manas Mukherjee, for their time and valuable comments. Moreover, I am thankful for all the help and motivation provided by Dr. Christoph Hufnagel, Dr. Maria Valado during these years. I also want to thank to Dr. Amir Shakouri for helping me with COMSOL simulations. And I also like to acknowledge my fellow classmates, lab-mates and friends for their continuous encouragement, support and stimulating discussions through out the four and half years we spent together in NTU. I also would like to express my love and gratitude for my family: my parents, brother and sisters for their unyielding love, physical and mental support throughout my Ph.D. and my whole life. This accomplishment would not have been possible without all of them. Thank you.

...

Contents

Abstract	iii
Acknowledgements	v
List of Figures	ix
List of Tables	xiii
List of Abbreviations	xv
1 Introduction	1
1.1 Introduction	1
2 Superconducting Atom Chip Experimental Setup	5
2.1 Introduction	5
2.2 Laser System	5
2.3 Magnetic Field Sources	9
2.4 Vacuum System	11
2.5 Rubidium Atom Source	12
2.6 Cryogenic System	12
2.7 Superconducting Atom Chip	13
2.8 Cooling and Trapping Procedures	16
2.8.1 Magneto Optical Trap	16
2.8.2 Lower and Upper Magnetic Traps	16
2.8.3 Superconducting Vortex Traps	17
2.9 Optical Manipulation Laser Setup	18
2.9.1 Heating Laser Setup	18
2.9.2 Digital Micromirror Device (DMD)	18
2.10 LabVIEW Computer Control System	22
2.11 Imaging and Analysis	26
3 Theory of Superconductor and Superconducting Vortex Traps	29
3.1 Introduction	29
3.2 London Equations	29
3.3 Ginzburg-Landau Theory	30
3.4 Critical State Models of Vortex Distribution	34
3.4.1 Supercurrent from External Field Pulse	35
3.4.2 Distribution of Supercurrent and Remanent Magnetic Field	35
3.4.3 Magnetic Traps from Remanent Field	36
3.5 Discussion	40

4	Superconducting Square Trap for Cold Atoms	41
4.1	Introduction	41
4.2	Superconducting Square Trap Experiment	41
4.2.1	Superconducting Square Trap	42
4.3	Probing Magnetic Field of Vortices with Ultracold Atoms	43
4.3.1	Magnetic Field Distribution Perpendicular to Surface	43
4.3.2	Magnetic Field Distribution Parallel to Surface	44
4.4	Discussion	47
5	Optically Tailored Magnetic Potentials Based On Superconducting Vortices	49
5.1	Introduction	49
5.2	Optical Effect on Superconductors	49
5.3	Laser Heating Effect on Superconductors	50
5.3.1	Heat Absorption and Temperature Rise	50
5.3.2	Laser Heating Effect on YBCO Z-shaped Structure	53
5.3.3	Laser Heating Effect on YBCO Square Structure	54
5.3.4	Heat Diffusion in Superconducting Square	58
5.4	Tailored Magnetic Potentials Based on Optical Manipulation of Superconducting Vortex Structures	69
5.4.1	Manipulation of Single Vortex Trap into Two Vortex Traps	70
5.4.2	Probing Superconducting Vortex Magnetic Field with Atoms After Laser Exposure	70
5.4.3	Manipulation of Single Vortex Trap into Array of Vortex Traps	71
5.4.4	Manipulation of Vortex Structure for Generating Tailored Trapping Potential	72
5.4.5	Manipulation of Vortex Structure for On-Chip Matter Wave Interferometry Application	73
6	Conclusion and Outlook	77
6.1	Conclusion	77
6.2	Outlook	78
A	Abbreviations Used for Optical and Electronic Elements	79
B	Characterization of Magnetic Coils	81
C	Car Batteries Current Supply	85
	Bibliography	87

List of Figures

2.1	Frequency scheme of $ 5P_{3/2}, F' = 2, 3\rangle$ in the D_2 transition of ^{87}Rb used for the cooling, repumping, imaging and optical pumping beam showing respective locking point.	6
2.2	Schematic diagram of the cooling and repumping optical setup on the lower breadboard.	7
2.3	Schematics diagram of optical setup on the upper breadboard for frequency locking, optical pumping and imaging.	8
2.4	a) Schematic diagram of six-way beam splitter for each of the MOT beams. b) Schematic diagram for adjusting optimal power for circular polarization needed for MOT.	9
2.5	Schematic of electronic circuit diagram for controlling and adjusting high currents required for trapping and manipulating atoms. .	10
2.6	Schematic of electronic circuit diagram for high current car batteries setup for inducing high density superconducting vortices with external magnetic field.	11
2.7	Illustration of vacuum system in superconducting atom chip main setup for trapping and manipulating of ultracold atom.	12
2.8	a) Picture of wires connection to atom chip through gold pin from external sources. b) Picture of atom chip mounted and secured on cold finger.	13
2.9	a) Schematic diagram of superconducting atom chip structures. Zoom in b) Superconducting square structure c) Z-wires of various dimensions and a dimple wire.	15
2.10	Drawing of our standard MOT setup showing a pair of anti-Helmholtz coils and three pairs of counter-propagating 780 nm laser beams. The distance between the atomic cloud and the atom chip in MOT stage is 35 mm	16
2.11	Diagram of coils showing MOT coils and transfer coils used for magnetic trapping of the ultracold atoms. Three pairs of bias coils produce homogeneous bias fields in x, y and z-direction. The transfer coils produce quadrupole field and used to transfer atoms closer to the region of interest on the chip structures together with bias coils.	17
2.12	Schematic diagram and picture of heating laser setup; the AOM controls the pulse time and power of the beam and the beam shaping and light patterning of laser are carried out by the DMD.	19
2.13	The image of a DMD under an electron microscope. The mirrors are separated by $10.8\mu\text{m}$ from center to center and connected to the mount from the tube in the middle. The image at the right shows the mount when one mirror is removed.	19

2.14	Picture of a digital micro-mirrors device (DMD), the light is reflected to elsewhere and discarded in Off-state and the light is collected in direction of On-state to create desired patterns.	20
2.15	Calibration of DMD patterns with a CCD. The right picture shows the test image that is generated for the DMD. The resulting image is captured with the CCD camera and shown in the left picture. . .	21
2.16	Computer generated DMD patterns of a bright ring, a dark ring, two off-axis rectangles and a line used for manipulating the vortex traps.	21
2.17	LabVIEW sub-programme showing the experimental sequences. .	23
2.18	a)Current ramping to the MOT coils at compressed MOT stage (3rd row) shown in Fig. 2.17. b)Frequency ramping to detune the cooling beam at molasses stage (6th row) shown in Fig. 2.17.	24
2.19	LabVIEW main programme to execute the pre-loaded sequences of the sub-programs.	25
2.20	Illustration of absorption imaging setup of our experiment.	26
3.1	Illustration of normal (N) and superconducting (S) interface showing magnetic field (B) penetration and superconducting charge density n_s variation where λ is penetration depth, ξ is coherence length and ψ_∞ is a fully ordered state superconducting.	31
3.2	Physical parameters of the superconducting slit used for sheet current model.	36
3.3	Illustration of a vortex current I induced by an external magnetic field pulse B_{ext} inside a superconducting square structure.	37
3.4	Simulations of remanent current for external magnetic field pulse of $B_{ext} = 0$ to B_{max} to 0 with $B_{max} = 2B_c, 2.4B_c$ and $3B_c$	37
3.5	Simulations of magnetic trap using $B_{ext} = 0$ to $2.4B_c$ to 0 a) A single trap formed at the edge of the structure with $B_x^{bias} = 0.173B_c$ b) A single trap formed above the centre of the structure with $B_z^{bias} = 0.2B_c$	38
3.6	Simulations of magnetic trap using two loading pulses of $B_{ext} = 0.8 B_c$ and $B_{ext} = -0.4 B_c$ on a superconducting disk structure. A self-sufficient trap is formed above the disk center.	39
3.7	Simulations of magnetic trap using loading pulses of $B_{ext} = 0$ to $1.2 B_c$ to $-0.6 B_c$ to 0 on a superconducting ring structure using bias field $0.06 B_c$. A ring trap is formed above the ring structure.	39
4.1	Plot of the atom number in the square trap with corresponding trapping time (blue) with a fitted exponential curve (red).	42
4.2	Vortex distribution from Magneto Optical Imaging	43
4.3	Absorption images of atoms with increasing bias field in perpendicular to superconducting square surface. The upper cloud is a reflection from the chip surface. The two clouds are getting closer with increase in bias field as the cloud moves closer towards the surface.	44

4.4	Graph of position of atoms vs increasing bias field perpendicular to superconducting square surface. The positions are measured from the surface of the chip.	45
4.5	Absorption images of atoms vs increasing positive bias field in parallel to superconducting square surface. The upper cloud is a reflection from the chip surface. The two clouds are getting closer with increase in bias field as the cloud moves closer towards the surface.	45
4.6	Graph of atoms vs increasing bias field parallel to superconducting square surface. The positions are measured with reference to the atom cloud position with zero bias field.	46
5.1	Illustration of surface heating by laser light. The atom chip has a 800 nm layer of YBCO on top of the YSZ substrate.	50
5.2	Graph of surface temperature rise vs laser pulse time for an absorption power of 100 mW on YBCO square structure of 1 mm ² . . .	52
5.3	Graph of power vs resistance for laser exposure of 200 ms on a Z-shaped superconducting structure.	54
5.4	Graph of radius of atom cloud vs laser exposure time for 20 to 80 mW laser light shone on half of the 1 mm ² YBCO square.	55
5.5	Graph of radius of atom cloud vs laser power for 40 ms exposure time due to laser light shone on half of the 1 mm ² YBCO square. . .	55
5.6	Graph of YBCO critical current density vs temperature for different samples.	56
5.7	Graph of atoms number vs laser pulse time for 20 to 80 mW laser light shone on half of the 1 mm ² YBCO square and half without laser illumination.	57
5.8	Simulation of heat diffusion due to laser illumination on one half of the superconducting square for 5 ms and the corresponding cross section temperature profile of the whole square.	59
5.9	Simulation of heat diffusion due to laser illumination on one half of the superconducting square for 100 μ s and the corresponding cross section temperature profile of the whole square.	60
5.10	Simulation of heat diffusion due to cross pattern laser illumination on the center of the superconducting square for 1 ms and the corresponding cross section temperature profile cut across $y = 250 \mu$ m above the bottom.	61
5.11	Simulation of heat diffusion due to cross pattern laser illumination on the center of the superconducting square for 100 μ s and the corresponding cross section temperature profile cut across $y = 250 \mu$ m above the bottom.	63
5.12	Simulation of heat diffusion due to a ring pattern illumination of 200 μ m inner radius 100 μ m thick ring on the superconducting square for 1 ms and the corresponding cross section temperature profile.	65

5.13	Simulation of heat diffusion due to a ring pattern illumination of 200 μm inner radius 100 μm thick ring onto the superconducting square for 100 μs and the corresponding cross section temperature profile.	66
5.14	Simulation of heat diffusion due to ring pattern illumination of 200 μm inner radius 100 μm thick ring on the superconducting square for 1 μs and the corresponding cross section temperature profile.	67
5.15	Graph of heat diffusion in superconducting square due to heating of half square to 87 K temperature and corresponding diffusion length taken at 80 K temperature for various laser exposure time.	68
5.16	Absorption images of atom cloud for 200 μm line of laser light cutting in the center of superconducting square with fix power and increasing exposure time from 0 to 100 ms in 20 ms step.	70
5.17	Absorption images of atom cloud for 200 μm line of laser light cutting in the center of superconducting square with fix power for increasing bias field (0G, 3.5G, 10.3G, 17.4G). The upper cloud is reflection from the chip surface.	71
5.18	a) Absorption images of four atomic clouds after exposure from cross pattern laser light in the center of superconducting square. b) The corresponding DMD pattern of 200 $\times$ 200 μm cross.	71
5.19	Illustration of superconducting vortex lattices formed on superconducting square from laser interference pattern.	72
5.20	a) Absorption image of atom cloud for laser light with dot in the center and a line cut towards edge of superconducting square. b) The corresponding ring shape DMD laser light pattern.	73
5.21	Calculated absolute magnetic field of the two-wire guide in the xy-plane.	74
5.22	a) Absorption image of ring shaped atomic cloud for ring laser light shone in the center of superconducting square. b) The corresponding ring shape DMD laser light pattern.	74
C.1	Calibration of the hall probe voltage vs the current for car batteries.	85

List of Tables

5.1	Destruction of superconductivity with laser light, illustrating rise in temperature and reduction of superconducting transition temperature T_c	53
A.1	List of the abbreviations of optical and electronic elements used in this thesis.	79
B.1	Table of the power supplies models and corresponding maximum voltage and current for supplying current in the relevant magnetic coils	81
B.2	MOT coils measured current and hall probe voltage v.s. computer analogue voltage.	82
B.3	Transfer coils measured current and hall probe voltage v.s. computer analogue voltage.	82
B.4	Bias coils (B_{bias}^x) measured current and hall probe voltage v.s. computer bias analogue voltage.	83
B.5	Bias coils (B_{bias}^y) measured current and hall probe voltage v.s. computer bias analogue voltage.	83
B.6	Bias coils (B_{bias}^z) measured current and hall probe voltage v.s. computer bias analogue voltage.	83
B.7	Table showing the physical characterisation parameters for MOT, transfer and bias coils.	84
C.1	Measured hall probe voltage of 12 V car batteries connected in series.	86

List of Abbreviations

BEC	B ose- E instein C ondensate
YBCO	Y ttrium B arium C opper O xide
MMD	D igital M icro-mirror D evice
ECDL	E xternal C avity D iode L aser
TA	T apered A mplifier
PBS	P olarizing B eam S plitter
AOM	A cousto- O ptic M odulator
FP	F iber P ot
FA	F iber A daptor
MOT	M agneto O ptical T rap
WOP	W alk- O ff P olarizer
MOSFET	M etal O xide S emiconductor F ield E ffect T ransistor
IGBT	I nsulated G ate B ipolar T ransistor
TTL	T ransistor T ransistor L ogic
ES	E mergency S top
SSR	S olid S tate R elay
TEC	T hermo- E lectric C ooler
UHV	U ltra H igh V acuum
LIAD	L ight- I nduced A tomical D esorption
TSP	T itanium S ublimation P ump
YSX	Y tttria S tabilized Z irconia
CCD	C harge C oupled D evice
TOF	T ime- O f- F light
GUI	G raphical U ser I nterface
PB	P ulse B laster
LED	L ight E mitting D iode
MOI	M agneto O ptical I maging
SQUID	S uperconducting Q Uantum I nterference D evice

*Dedicated to my family for supporting my adventure in
Physics...*

Chapter 1

Introduction

1.1 Introduction

After the discovery of laser cooling and trapping of atoms in the 1980s, atom chips have emerged as one of the promising candidates to miniaturize the physical implementation of atomtronic devices [Keil et al. 2016]. They are designed and fabricated with complex micro-structures to produce versatile magnetic fields for trapping, cooling and manipulating ensembles of ultra-cold atoms in the vicinity of the surface [Sidorov and Hannaford 2011]. The versatility and enhanced accuracy of the atom chip enable not only new technology but also a variety of novel fundamental studies [Keil et al. 2016]. The first Bose-Einstein Condensate (BEC) was achieved with atom chips using metallic wires [Hänsel et al. 2001, Ott et al. 2001]. Soon after that BEC was produced on atom chips using permanent magnets [Sinclair et al. 2005, Fernholz et al. 2008] and superconductors [Roux et al. 2008a]. Atom chips were also used to study atoms-surface interactions [Fortágh et al. 2002], to build a surface ion trap [Stick et al. 2005, Kunert et al. 2014], to realize an interferometer [Schumm et al. 2005a] and atomic clocks [Treutlein et al. 2004, Lacroute et al. 2010]. They were also used to implement various atomic optical elements such as mirrors [Savalli et al. 2002], lenses [Smith et al. 2008] and diffraction gratings [Günther et al. 2007].

However, atoms trapped in normal conducting atom chips are limited by spin-flip losses, heating and decoherence [Scheel and Hinds 2011, Fortágh et al. 2002]. Specifically, fluctuations in the magnetic field caused by noises can cause atoms in a magnetic trap to transit from a trapped to an untrapped magnetic sub-level [Henkel, Pötting, and Wilkens 1999]. The two main noises leading to spin-flip losses are technical noise and thermal noise (or Johnson-Nyquist noise). The technical noise is generated due to fluctuations in the current from external power sources which disturbs the generated magnetic field that traps the atoms [Scheel et al. 2006]. Thermal noise is induced by the fluctuation of electromagnetic fields due to the random motion of the charge carriers inside an electrical conductor [Jones et al. 2003]. Moreover, the trapped atoms can excite to higher vibrational state if the thermal noise produce frequency components at the harmonics of the

trapping frequency. The excitation of atoms can also rise the overall temperature of atom cloud and results in heating [Henkel and Wilkens 1999, Leanhardt et al. 2003]. Those atoms will be lost from the trap if the temperature of atoms rises above the trapping potential depth [Leanhardt et al. 2003]. The fluctuation of magnetic fields also affects the energy of the Zeeman sub-level resulting in decreasing the coherence time for superposition state between Zeeman sub-levels [Henkel et al. 2003]. In order to overcome these limitations, several different experiments were carried out such as trapping atoms near insulators [Lin et al. 2004], using alloys wires [Dikovskiy et al. 2005], permanent magnets [Whitlock 2007] or superconductors [Fermani et al. 2010].

Superconducting atom chips edged out the other methods because they can suppress spin-flip loss, heating and decoherence all at once. The spin-flip loss rate resulting from thermal noise is reduced for atoms trapped near the superconductors (niobium [Hohenester et al. 2007, Skagerstam et al. 2006] and YBCO [Fermani et al. 2010]). Moreover, several orders of magnitude increase in the lifetime was reported for an atomic cloud trapped near superconductors [Fermani et al. 2010, Skagerstam et al. 2006, Skagerstam and Rekdal 2007]. Furthermore, the heating rate of atoms trapped using superconducting chip was shown to be reduced when compared to metals [Fermani et al. 2010]. Moreover, it is estimated that the decoherence of atoms is suppressed when they are $1\ \mu\text{m}$ from the superconducting chip surface as compared to a normal conductor [Skagerstam et al. 2006]. The spin-flip loss resulting from technical noise can also be eliminated since superconductors can trap atoms without any continuous external current source. A persistent current can be induced in a superconducting closed loop through field cooling [Farach and Creswick 1995, Mukai et al. 2007] and the magnetic field from the persistent current can be used for trapping atoms. Vortex currents can be induced in type-II superconductors by applying a magnetic field pulse above first critical field B_{c1} but below second critical field B_{c2} . The vortex currents are mediated by superconducting vortices and atoms can be trapped near superconducting structures such as strip [Zhang et al. 2010a], disk and ring structures [Zhang et al. 2012a] by mean of vortex current traps. In addition, the cryogenic environment needed for operating the superconducting atom chip reduces the vacuum pressure in the experiment, hence the lifetime of the trapped atoms can be increased up to 10 minutes [Dumke and Christoph 2018].

The first superconducting atom chip using niobium (Nb, critical temperature $T_c = 9.2\ \text{K}$) at liquid helium temperature was realized in 2006 [Nirrengarten et al. 2006]. Soon after that, a successful trapping of ultracold atoms with magnesium diboride (MgB_2) superconducting atom chip (T_c of $39\ \text{K}$) was reported [Mukai et al. 2007]. Our group fabricated a superconducting atom chip based on yttrium barium copper oxide (YBCO, T_c of $87\ \text{K}$) in 2008 [Müller et al. 2008a]. The superconducting transition temperature T_c of our chip is higher than the liquid nitrogen temperature (77K) that gives our cryogenic system a cost-effective advantage

compared to a liquid helium system [Cano et al. 2011, Jessen et al. 2014]. YBCO is a type-II superconductor in which vortex currents can be induced by external magnetic fields. We showed that magnetic micro-traps can be generated by vortex currents from a superconducting strip in our atom chip [Müller et al. 2010b]. In our previous projects, the vortex currents were programmed to generate complex spatial current patterns to create complex trapping potentials [Müller et al. 2010]. A self-sustaining trap using only vortex current from superconducting square structure was also realized on our atom chip [Siercke et al. 2012a].

Our previous projects were focused on generating the various vortex base magnetic traps for ultracold atoms by varying the external magnetic field pulses [Müller et al. 2010a, Zhang et al. 2010b, Müller et al. 2010c, Siercke et al. 2012b]. However, our current atom chip has limited number of structures fabricated on the chip and reconfigurability of the trapping potential is restrained. Since replacing the atom chip in cryogenic and vacuum environment is not feasible in short period of time, a way to actively modify geometries of superconducting structures will enhance the reconfigurability of the superconducting vortex traps. One of the effective ways to reconfigure the superconducting structures is by manipulating the superconductivity and vortex structures optically. The advantage of this non-destructive technique is that both superconductivity and the original geometry can be restored back after re-cooling the atom chip below the critical temperature. Hence new arbitrary superconducting geometries can be tested readily.

Furthermore, the precision of manipulation of these vortices have been demonstrated up to a single vortex [Veshchunov et al. 2016]. Thus, it is possible to create desired potentials with great flexibility and precision. The micro-structured surface traps generated from vortices can be used for quantum simulations such as Bose-Hubbard model [Romero-Isart et al. 2013] for fundamental studies. The ability to tailor the surface traps optically also opens many further opportunities to couple cold atoms with solid state devices for quantum state transfer and information processing [Sørensen et al. 2004, André et al. 2006] due to the long coherence time of cold atoms. The coupling with superconducting devices such as SQUID and on-chip interferometer applications will further draw researchers attention to optically tailorable micro structured vortex traps. This thesis gives a comprehensive account of various superconducting vortex trapping potentials and generation of tailored trapping potentials for ultracold atoms by optically manipulating superconducting vortices.

The thesis is structured in the following way. Chapter 1 introduces the superconducting atom chip and superconducting vortex traps. In Chapter 2, the experimental setup is discussed and it includes the optical apparatus, vacuum system, electronics, computer control, image acquisition, heating laser setup. The theory of superconductors is covered in Chapter 3. This chapter also introduces the critical state model describing the mesoscopic behavior of induced vortices inside the superconductor. These theoretical descriptions serve as a background

knowledge for our experimental realization of magnetic micro-traps using superconducting vortices. Chapter 4 discusses the configuration and characterization of various trapping potentials on a square structure of our superconducting chip. Chapter 5 describes optical manipulation of superconducting vortices on the superconducting square for designing tailored potentials and shows that arbitrary exchangeable potentials can be realized using this technique. The thesis is concluded with the discussion of the further developments and future prospects of superconducting atom chip in Chapter 6.

Chapter 2

Superconducting Atom Chip Experimental Setup

2.1 Introduction

This chapter describes different components of the experimental setup. The first parts, section 2.2 to 2.5, focus on the setup for cooling atoms down to μK temperatures. The later parts, section 2.6 and 2.7, describe the superconducting atom chip used for trapping cold atoms. In section 2.8, different stages of cooling and trapping of cold atoms are discussed. Section 2.10 explains the experimental sequences programmed with LabVIEW. In section 2.9, the optical manipulation scheme of superconducting structures using an infrared laser and a Digital Micromirror Device (DMD) is explained. The last section 2.11 discusses the imaging system and how data are analyzed with MATLAB.

2.2 Laser System

The laser system in our experiment comprises two lasers, one for addressing the cooling and one for addressing the repumping transition. The cooling laser system is a commercial laser from Toptica - TA-100-780-02008 and consists of an external cavity diode laser (ECDL) and a tapered amplifier (TA). The ECDL is configured to produce the desired wavelength with 30 mW of output power, which is amplified by the TA to a total output power of 1 W. The repumper laser is a Toptica - DL100 with output power of 30 mW.

The optical system is designed to be compact and consists of two vertically stacked optical breadboards. The upper breadboard houses the optical setup for the imaging beam, optical pumping beam and spectroscopy for cooling and repumping transitions. The lower breadboard contains the cooling and repumper beams which are fiber coupled to the main experiment. The optical setup is configured according to frequency scheme shown in Fig. 2.1. The frequency of the

cooling laser is locked at a cross-over transition and the repumper frequency is locked at the crossover transition ^{87}Rb ($|5S_{1/2}, F = 1\rangle$ to $|5P_{3/2}, F' = 1, 2\rangle$) which is 80 MHz away from the repumping transition. The frequency locking methods are explained in details at the upper layer optical setup section. The schematic diagrams of the lower and upper optical setups are shown in Fig. 2.2 and Fig. 2.3 respectively.

Figure 2.1: Frequency scheme of $|5P_{3/2}, F' = 2, 3\rangle$ in the D_2 transition of ^{87}Rb used for the cooling, repumping, imaging and optical pumping beam showing respective locking point.

The cooling laser is split with a polarizing beam splitter (PBS) into two paths in the lower breadboard as shown in 2.2. The transmitted beam passes twice through an acousto-optic modulator (AOM) (AOM1, + 2x105 MHz) in a double pass configuration and 210 MHz is added to the frequency of the laser. This laser beam is set to address the Rubidium (Rb) cooling transition ^{87}Rb ($|5S_{1/2}, F = 2\rangle$ to $|5P_{3/2}, F' = 3\rangle$). The cooling beam is coupled to a polarization maintaining fiber mounted to a fiber port (FP) FP1. The reflected beam is directed to the upper breadboard and used for optical pumping, imaging, spectroscopy.

Fig. 2.2 shows the repumper laser output split into two paths with a PBS in the lower breadboard. The reflected beam goes through an AOM (AOM2, + 80 MHz) which shifts its frequency by +80 MHz, bringing it on resonance with the repumping transition. The frequency of the beam is set to address the repumping transition ^{87}Rb ($|5S_{1/2}, F = 1\rangle$ to $|5P_{3/2}, F' = 2\rangle$). After the AOM, the repumping beam is overlapped with the cooling beam, before being coupled into the fiber at FP1. The transmitted repumping beam is directed to the upper breadboard for spectroscopy and frequency locking.

Figure 2.2: Schematic diagram of the cooling and repumping optical setup on the lower breadboard. Abbreviations for optical and electrical elements are listed in Appendix A.

The output beam from FP1 has $\sim 214 \text{ mW}$ in which $\sim 210 \text{ mW}$ is from the cooling beam and $\sim 4 \text{ mW}$ from the repumper. The beam goes through a six-way beam splitter as shown in Fig. 2.4.a). Three pairs of counter-propagating laser beams are needed for Magneto-Optical Trapping (MOT) to provide radiation pressure from three dimensions. The pairs are labeled as 1 and 2, 3 and 4, 5 and 6. The power going into each pair can be adjusted with half-wave plates installed before the walk-off polarizers (WOP). The beams are coupled to non-polarization maintaining fibers and sent to the main experiment through cage optical setups shown in Fig. 2.4.b).

In the optical cage setup, the six individual beams are out-coupled with a fiber adaptor (FA). The beam goes through a quarter-wave plate, a half-wave plate, and a PBS to obtain maximum output power and clean polarization. The beam is collimated through a lens (50 mm in diameter and 125 mm in focal length) inserted

after the PBS. Another quarter-wave plate is installed to select an appropriate circular polarization for the MOT.

Figure 2.3: Schematics diagram of optical setup on the upper breadboard for frequency locking, optical pumping and imaging. Abbreviations for optical and electrical elements are listed in Appendix A.

The cooling beam that is directed from the lower breadboard to the upper breadboard is split into two parts with a PBS as shown in 2.3. The reflected beam is used for spectroscopy and locking purposes. This beam is frequency modulated by an AOM (AOM5, +87 MHz) via a lock-in amplifier and 87 MHz is added to 1st order of outgoing beam. The 1st order beam is fiber-coupled to FP4 and sent to a saturation spectroscopy setup (TEM Messtechnik - CoSy 5.0). The frequency modulated absorption output signal from the CoSy is sent to a proportional integral (PI) controller. The PI controller processes the signal and gives out an error signal. The error signal is used for providing feedback to piezoelectric ceramic crystal (PZT) of the cooling ECDL laser to lock the laser frequency. The 1st order beam is locked to the crossover peak ($|5S_{1/2}, F = 2\rangle$ to $|5P_{3/2}, F' = 2, 3\rangle$) of the D_2 transition of ^{87}Rb . The output laser frequency is stabilized at 87 MHz below the crossover transition as shown in Fig. 2.1.

The transmitted beam, in turn, is split into two with another PBS. These reflected beam and transmitted beam are used for imaging and optical-pumping respectively. The reflected beam goes through an AOM (AOM3, +2x110 MHz) twice in double pass configuration. The second 1st order beam is on resonance to ($|5S_{1/2}, F = 2\rangle$ to $|5P_{3/2}, F' = 3\rangle$) of the D_2 transition of ^{87}Rb for imaging the atoms as shown in Fig. 2.1. This beam is coupled to FP2 and sent to the imaging setup in the main experiment. The last transmitted beam is used for optical pumping and passes through an AOM (AOM4, -46 MHz) and -1st order is coupled to FP3. This optical pumping beam together with repumping beam is used

Figure 2.4: a) Schematic diagram of six-way beam splitter for each of the MOT beams. b) Schematic diagram for adjusting optimal power for circular polarization needed for MOT. Abbreviations for optical and electrical elements are listed in Appendix A

to pump atoms into $|F = 2\rangle$ to $|F = 2, m_F = 2\rangle$ quantum state for magnetic trapping.

The repumping beam directed to the upper breadboard is used for spectroscopy and frequency locking purposes as shown in Fig. 2.3. The beam passes through a PBS and the reflective beam is directed through a Rubidium cell and reflected back to the cell to get doppler-free saturation spectroscopy signal. The doppler-free signal is collected with a photodiode (PD) and sent to a PI controller. The PI controller gives out an error signal for frequency locking to the crossover transition ^{87}Rb ($|5S_{1/2}, F = 1\rangle$ to $|5P_{3/2}, F' = 1, 2\rangle$).

2.3 Magnetic Field Sources

Our experiment has a total of six pairs of magnetic coils; MOT coils, transfer coils and compensation coils and three pairs of (x, y, z) bias coils. Trapping and transferring of atoms requires high magnetic fields and high current power supplies are used to provide currents of up to 165 A to the coils. The electronic circuit shown in Fig. 2.5 is designed to control high current pulses safely and effectively. The calibrations of the magnetic coils of the setup are shown in Appendix B.

The currents run through the coils can be controlled with a metal-oxide-semiconductor field-effect transistor (MOSFET) (IXYS - IXFN230N10). The MOSFET driver provides the gate voltage for the MOSFET through computer control analog voltage and controls the amount of current. The Hall probe provides feedback to the

MOSFET drive in case of an increase in resistance from heating. The MOSFET driver adjusts the gate voltage accordingly to provide a constant current through the coils. The switching of the current is carried out with an insulated-gate bipolar transistor (IGBT) (PRX - CM600HA-24A) through computer control transistor-transistor logic (TTL) signal to switch the current in μs range. The voltage of the power supply is controlled by an analog voltage from a computer card to provide appropriate voltages for the desired magnitude of the current pulses. Other electronic components such as a diode, a high power resistor and a few varistors are used to prevent damage from a high back EMF due to fast switching of currents through the coils.

Figure 2.5: Schematic of electronic circuit diagram for controlling and adjusting high currents required for trapping and manipulating atoms.

Some experiments require even higher magnetic fields and thus currents higher than 165 A are needed. The MOT coils shaded in the red box, shown in Fig. 2.5 can be switched to a battery setup shown in Fig. 2.6. The six batteries in the setup can be connected in series to provide ~ 260 V for those experiments. They can be connected to give out 0 V to 72 V in 12 V steps. The current is controlled with two relays (Tyco Electronics - EV200HAANA) and a MOSFET. The two relays are used for safety purposes and connected to an emergency stop (ES) button as well as a dead-man switch. A pulse generator circuit generates pulses with variable amplitude and pulse time respectively via a Solid State Relay (SSR) (Crydom - DC60S5) as shown in Fig. 2.6. The Hall Probe provides feedback to the MOSFET driver to stabilize the signal. This signal is sent to the MOSFET as the gate voltage. The MOSFET driver is equipped with an opto-isolator that turns on only with a mechanical relay which is powered by a 15 V supply for safe operation. Currents of 0 to 260 A can be generated by adjusting the gate voltage of MOSFET in this setup. A thermoelectric cooler (TEC) is used to cool down the MOSFET due to heating from high currents. The cooling scheme is required for operating multiple pulse sequences. The current calibration of the setup is shown in Appendix C.

Figure 2.6: Schematic of electronic circuit diagram for high current car batteries setup for inducing high density superconducting vortices with external magnetic field.

2.4 Vacuum System

Cold atoms experiments require Ultra-High Vacuum (UHV) to minimize the atom loss due to collision from background gases. Fig. 2.7 shows the vacuum system with a glass cell housing a cold finger. The atom chip is secured to the cold finger. The cold finger is placed in the vacuum through the top of the chamber to cool the superconducting atom chip below the critical temperature. A glass cell was chosen because it provides maximum optical access for atom collection and manipulation. The electrical feed-through connections to the atom chips are routed at the sides of the vacuum chamber. UHV is achieved by two UHV pumps and an ionization gauge is used to read out the vacuum pressure.

The two UHV pumps are an ion pump (Varian - VacIon Plus 75, CF6" Starcell) and a titanium sublimation pump (TSP) (TSP Filament Cartridge on a 2 3/4" CFF - 9160050). The ion pump is turned on continuously to maintain the vacuum pressure below 4×10^{-10} mbar. The TSP deposits titanium layers in the vacuum chamber to serve as pumping surface for adsorbing remaining residual gases inefficiently pumped by the ion pump. Over time, the titanium layer will saturate, which will result in a decreasing pumping speed and increase in pressure. The TSP is therefore turned on at certain intervals to replenish the titanium coating for effective pumping. The ionization gauge (Agilent Technologies - UHV- 24P

Bayard-Alpert Ion Gauges) is fitted in the vacuum system to measure the pressure.

Figure 2.7: Illustration of vacuum system in superconducting atom chip main setup for trapping and manipulating of ultracold atom.

2.5 Rubidium Atom Source

Atoms in the glass cell are continually continuously attracted and collected by the ion pump, thus the number of atoms in the cell decreases gradually. The rubidium dispensers (Alvasources - AS-6-Rb-240-C) are used as an atom source to refill the atoms every few months. We apply currents of 2.5 to 4.0 A to dispense atoms into the vacuum until vacuum pressure reaches 2×10^{-9} mbar. After the dispensers are switched off, some of the atoms are collected by the ion pump. The remaining rubidium atoms gradually absorb to the surface of the glass cell and pressure goes back to the initial value of below 4×10^{-10} mbar after a few minutes.

The light-induced atomic desorption (LIAD) is used to desorb rubidium atoms from the surface during the MOT stage. An array of 6 UV LEDs (Roithner LaserTechnik - RLT-MIL410-12V-30, violet, 410-415nm) is used for the LIAD. And the light from LEDs is illuminated near the glass cell to increase the number of atoms available for cooling.

2.6 Cryogenic System

The cryogenic system consists of a liquid nitrogen tank (Taylor Wharton - XL 160) and a cold finger. The cold finger is a flow cryostat in which the liquid nitrogen will flow through to provide cooling for the atom chip. Liquid nitrogen is

filled and stored in a pressurized tank. The cold finger is connected to the liquid nitrogen tank to maintain the cooling temperature of ~ 77 K. Clusters of insulated wire from external sources are inserted through the electrical accesses and clamped to gold pin beside the cold finger as shown in Fig. 2.8.a). These wires are clamped with a few copper rings to the side of the cold finger to minimize the heat transfer from room temperature external sources.

The atom chip is mounted on the cold finger as shown in Fig. 2.8.b). A chip holder is screwed to the cold finger and the atom chip is positioned on the chip holder with four copper clamps. An indium layer is also placed in between to ensure good thermal contact. The chip is then secured to the holder with four stainless steel screws. A ring structure made of macor houses the gold pins connection to insulate electrical contacts from the cold finger. The gold pins are then connected to gold pads on the atom chip with gold wires. The electrical connections to the structures on the chip is connected from these gold pads.

Figure 2.8: a) Picture of wires connection to atom chip through gold pin from external sources. b) Picture of atom chip mounted and secured on cold finger. Picture adapted from [Chan 2014].

2.7 Superconducting Atom Chip

The structures on our superconducting atom chip are used to trap and manipulate cold atoms near the surface of the superconductor. The design of the atom chip consists of a square structure and various sizes of Z-shaped wires together with a dimple wire as shown in Fig. 2.9.a). The chip was fabricated by an external company (Theva Duennschichttechnik) based on our design. The structures are made out of a high-temperature superconductor, yttrium barium copper oxide

(YBCO, molecular formula is $YBa_2Cu_3O_{7-x}$) patterned onto a $20\text{ mm} \times 20\text{ mm}$ yttria-stabilized zirconia (YSZ) single crystalline substrate.

The details structures are zoomed in to display the dimensions. Fig. 2.9.b,c) show a magnified view of the dotted rectangles in Fig. 2.9.a). All YBCO structures have a thickness of 800 nm . The square superconducting pad, shown in Fig. 2.9.b) has dimension of $1\text{ mm} \times 1\text{ mm}$. The three Z-shaped wire structures with different dimension are shown in Fig. 2.9.c). The sizes are $50\text{ }\mu\text{m}$, $200\text{ }\mu\text{m}$ and $400\text{ }\mu\text{m}$ with 5 mm length and separation of $20\text{ }\mu\text{m}$. A dimple wire of $200\text{ }\mu\text{m}$ width crosses perpendicularly to all the Z-shaped wires.

Figure 2.9: a) Schematic diagram of superconducting atom chip structures. Zoom in b) Superconducting square structure c) Z-wires of various dimensions and a dimple wire.

2.8 Cooling and Trapping Procedures

2.8.1 Magneto Optical Trap

The magneto-optical trap (MOT) consists of three sub-systems; laser system for cooling, magnetic system for trapping and vacuum system for isolation from the surrounding. The standard method to produce ^{87}Rb MOT is using three pairs of counter-propagating circular polarized laser beams and a pair of anti-Helmholtz coils [Foot 2005] as shown in Fig. 2.10. After an initial MOT stage, we increase the magnetic field of the coils drastically to achieve a high-density compressed MOT (CMOT). However, the temperature of the atoms also increases during the process. After that the atomic cloud is cooled down using molasses cooling in the absence of the magnetic field. This can be done by switching off the anti-Helmholtz coils and providing the constant magnetic field with a compensation coil to cancel out the earth magnetic field.

Figure 2.10: Drawing of our standard MOT setup showing a pair of anti-Helmholtz coils and three pairs of counter-propagating 780 nm laser beams. The distance between the atomic cloud and the atom chip in MOT stage is 35 mm.

2.8.2 Lower and Upper Magnetic Traps

After atoms are cooled down with molasses cooling, optical pumping beam and re-pumping beam are used to pump the ultracold atoms from the $|F = 2\rangle$ to the $|F = 2, m_F = 2\rangle$ quantum state. The atoms can be trapped in the magnetic field minima in the low-field seeking state. After that, the MOT coils are turned back

on to produce a quadrupole magnetic field potential. This trap is ($\approx 35\text{ mm}$) below the superconducting chip and is called the lower magnetic trap.

The atomic cloud is then transported closer to the superconducting chip using elliptical transfer coils. It is done by ramping up the magnetic field from the transfer coils adiabatically while maintaining the magnetic field from the lower trap MOT coils. After that, the magnetic field from the lower trap is ramped down adiabatically, maintaining the field from transfer coils. This trap is called the upper magnetic trap and the atomic cloud trapped in this trap is just ($\approx 2\text{ mm}$) below the superconducting chip.

2.8.3 Superconducting Vortex Traps

Figure 2.11: Diagram of coils showing MOT coils and transfer coils used for magnetic trapping of the ultracold atoms. Three pairs of bias coils produce homogeneous bias fields in x , y and z -direction. The transfer coils produce quadrupole field and used to transfer atoms closer to the region of interest on the chip structures together with bias coils.

The atomic cloud from the upper magnetic trap is loaded into micro traps of the atom chip using homogeneous bias fields from three pairs of (x , y , z) bias coils. The cold atoms can be trapped with the superconducting structures either in a Z-shape or a square shape trap. The superconducting atom chip experiments are carried out in these traps. The atoms can be imaged with a CCD camera in-situ. The magnetic field can be turned off to get time-of-flight (TOF) measurements as well. The schematic drawing of the coils is shown in Fig. 2.11.

2.9 Optical Manipulation Laser Setup

This section discusses the optical setup for manipulating superconducting vortices. The 1064 nm laser was used to heat up a particular area of the superconducting square pad to clean up superconducting vortices. An arbitrary light pattern from a Digital Micromirror Device (DMD) can be mapped to the superconducting square to manipulate vortex patterns for shaping the desired trapping potential for cold atoms. The heating laser setup is discussed in Sec. 2.9.1 and arbitrary light patterns generation with DMD is explained in Sec. 2.9.2.

2.9.1 Heating Laser Setup

We use a commercial 1064 nm, 1.5 W laser (LSR1064ML) to manipulate superconducting vortices. The schematic and picture of the setup are shown in Fig. 2.12. The laser beam goes through an AOM (+80 MHz) for fast switching. The laser beam is focused with a 200 mm lens to the AOM to optimize the efficiency to 80% and the beam has power of 1.2 W after the AOM. After that, the output beam is collimated with 300 mm lens to match the dimension of an array of micro-mirrors in DMD. The beam from the AOM is then directed to the DMD to generate an arbitrary light pattern. The details of light shaping with DMD is discussed in Section 2.9.2. The DMD has an efficiency of about 50% for 1064 nm light and the maximum output from the DMD is measured about 600 mW. The 1st order reflected light from the DMD is collected with a 750 mm lens and an another 300 mm lens is used to map the light pattern on a square superconducting pad of 1 mm × 1 mm. The intensity and pulse time of the laser can be adjusted by the AOM to achieve the desired heating effect.

2.9.2 Digital Micromirror Device (DMD)

Background Theory

The Digital Micro-Mirror Device (DMD) is a spatial light modulator consisting of an array of fast switching micro-mirrors. Each micro-mirror can be tilted to ± 12 degrees by electrostatic attraction to reflect the light. The light is collected at 12 degrees to the normal and each mirror works as a pixel to generate light patterns collectively. The patterns are generated by a computer and loaded to the DMD. The commercial DMD is purchased from Texas Instruments and has dimensions of 8 × 4 mm². The micro-mirror pitch is 10.8 μm center to center with sub-micrometer slits between the mirrors. The measured reflection efficiency of the DMD in the setup for 1064 nm light is $\sim 50\%$.

Fig. 2.13 shows an image of the DMD under an electron microscope [Dudley and Dunn 2006]. The DMD functions as a blazed diffraction grating for coherent laser light. When all mirrors are tilted to the same state, a regular structure with

Figure 2.12: Schematic diagram and picture of heating laser setup; the AOM controls the pulse time and power of the beam and the beam shaping and light patterning of laser are carried out by the DMD.

Figure 2.13: The image of a DMD under an electron microscope. The mirrors are separated by $10.8\mu\text{m}$ from center to center and connected to the mount from the tube in the middle. The image at the right shows the mount when one mirror is removed. Picture adapted from [Dudley and Dunn 2006].

a spacing of $\sqrt{2} \times 10.8\mu\text{m}$ can be formed. For a blazed diffraction grating, the intensity distribution can be written as [Demtröder 2006],

$$I(\theta) = I_S \left[\frac{\sin[\pi \frac{b}{\lambda} \sin\theta]^2}{[\pi \frac{b}{\lambda} \sin\theta]^2} \right] \left[\frac{\sin[N\pi \frac{d}{\lambda} \sin\theta]^2}{[\pi \frac{d}{\lambda} \sin\theta]^2} \right] \quad (2.1)$$

where I_S is the intensity transmitted from the single slit, θ is the angle under which the intensity is observed and λ is the wavelength of the light. The number of the illuminated slits is given by "N", the spacing of grating is represented by "d" and the width of the slits is "b". The first fraction of the equation characterizes the diffraction of the single slit, and the second fraction describes the interference of the different slits. The location of the zeroth order only depends on the incident angle but all other orders depend on the grating pitch and the wavelength. We used the first order to generate the light patterns for the laser heating.

Optimization and Mapping

Figure 2.14: Picture of a digital micro-mirrors device (DMD), the light is reflected to elsewhere and discarded in Off-state and the light is collected in direction of On-state to create desired patterns. Picture adapted from [Allen 2017]

The details structure of ON and OFF state of DMD is shown in Fig. 2.14. The reflective beam is optimized by directing the incident beam to the center of the DMD with an arbitrary pattern loaded into the DMD. After that, lenses between the DMD and the CCD camera are adjusted to generate the sharp image of the pattern on the CCD. A test image from the DMD is projected to the CCD and lenses are further adjusted by monitoring the sharpness of the image on the computer. The resulting test image is shown in Fig. 2.15.

A transformation can be calculated with the coordinates from the DMD and the CCD. The coordinates in the DMD system (x' , y') and the coordinates in the CCD system (x , y), can be related by [Etzold 2010],

$$\begin{bmatrix} x' \\ y' \end{bmatrix} = \begin{bmatrix} a_{11} & a_{12} \\ a_{21} & a_{22} \end{bmatrix} \begin{bmatrix} x \\ y \end{bmatrix} + \begin{bmatrix} t_1 \\ t_2 \end{bmatrix} \quad (2.2)$$

The matrix components a_{ij} and the translation vector t_i can be extracted from the equation. The shape and position on the DMD can be mapped to the CCD. Some examples of computer-generated DMD patterns of a line of $200 \mu m$, two

Figure 2.15: Calibration of DMD patterns with a CCD. The right picture shows the test image that is generated for the DMD. The resulting image is captured with the CCD camera and shown in the left picture.

rectangles of $300 \times 400 \mu m^2$ and rings patterns of different dimensions are shown in Fig. 2.16.

Figure 2.16: Computer generated DMD patterns of a bright ring, a dark ring, two off-axis rectangles and a line used for manipulating the vortex traps.

After optimization and characterization with the CCD camera, the DMD images are mapped onto the superconducting square structure following the same procedures. The atom chip is 20 cm above the level of the DMD surface and the incident angle of the beam is 32 degrees from the normal of the square structure on the chip. The patterns on the DMD have been corrected for the elevation angle accordingly and desired patterns can be mapped to the square structure.

2.10 LabVIEW Computer Control System

The experimental sequences are carried out by LABVIEW programs using two types of cards in our computer system. Two analog cards (National Instruments - PCI-6713, 12 bits) has 8 channels and able to provide 0 to 10 V. The digital card (SpinCore PulseBlaster (PB)) is used for switching purpose which has 24 digital channels and provide TTL pulse of 3.3 V. Programs from NIST, Gaithersburg are adopted to interface LabVIEW cards with the hardware. We use a main program and sub-programs to control the experimental sequences. The sub-program executes if it is called by the main program. The sub-program shown in Fig. 2.17 controls sequences of MOT, CMOT, molasses and magnetic traps and the ramping stages are controlled by the sub-program shown in Fig. 2.18. Fig. 2.19 shows the main program which executes the pre-loaded sequences from the sub-programs.

Figure 2.17: LabVIEW sub-programme showing the experimental sequences.

(a)

(b)

Figure 2.18: a) Current ramping to the MOT coils at compressed MOT stage (3rd row) shown in Fig. 2.17. b) Frequency ramping to detune the cooling beam at molasses stage (6th row) shown in Fig. 2.17.

Figure 2.19: LabVIEW main programme to execute the pre-loaded sequences of the sub-programs.

2.11 Imaging and Analysis

We use the absorption imaging method to image the cold atoms. Two achromatic lenses are used in our imaging setup to minimize chromatic and spherical aberration as shown in Fig. 2.20. The first lens L1 is positioned at focal length distance away from the atomic cloud and the second lens L2 focuses the image on the charge-coupled device (CCD) camera. We use three imaging setups to capture the atomic clouds in different stages. The first setup (L1 = 76.2 mm, diameter = 25.4 mm; L2 = 100 mm, diameter = 50 mm) uses Pixelfly QE Camera to image the clouds at the MOT, molasses and the lower magnetic trap stages. The second setup (L1 = 75 mm, diameter 30 mm; L2 = 100 mm, diameter = 50 mm) uses another camera (Theta system - SIS1-s285M) to capture the clouds at the upper magnetic trap and near the surface of the superconducting atom chip with a small reflection angle. The third setup (L1 = 400 mm, diameter = 25.4 mm; L2 = 400 mm, diameter = 25.4 mm) uses another Pixelfly QE Camera to image the cloud near the surface of the chip with a large grazing angle to capture the elevated view of the cloud from below the atom chip.

Figure 2.20: Illustration of absorption imaging setup of our experiment.

second captured image serves as the background image

Two images are captured for analyzing. The atomic cloud (cloud image), $I_{cloud}(y, z)$ is taken first for 100 μs exposure with the imaging beam. Another image (background image), $I_{bkg}(y, z)$ is taken 1 s after the first image. The atomic cloud disappears after 1 s and the second captured image with the imaging beam serves as the background image. A logarithmic ratio between the intensities of two images gives an optical depth (OD) [Pyragius 2012, Smith et al. 2011] and it can be written as

$$OD(x, z) = \ln \frac{I_{bkg}(x, y)}{I_{cloud}(x, y)} \quad (2.3)$$

For an imaging beam intensity below saturation, the OD can be expressed as

$$OD(x, z) = n(x, z)\sigma \quad (2.4)$$

The absorption cross-section σ depends on the detuning of the imaging beam from resonance. For on resonance imaging beam, with $\lambda = 780 \text{ nm}$, it becomes

$$\sigma = \sigma_0 = \frac{3\lambda^2}{2\pi} = 0.29 \mu\text{m}^2 \quad (2.5)$$

$n(x, z) = n(x, z)$ is the atomic column density. $n(x, z) = \int n(x, y, z) dy$ in our case and it can be acquired by integrating along the imaging beam. The information such as spatial density distribution, atom number, phase space density, size can be obtained from $n(x, z)$. The total atom number, N can be calculated through the numerical sum over all pixels,

$$N = \frac{\Delta_x \Delta_z}{\sigma} \sum_{i,j} OD(x_i, z_j) \quad (2.6)$$

where Δ_x and Δ_z are the object size of one pixel. In our case, $\Delta_x = \Delta_z = 11 \mu\text{m}$ for the first imaging setup and $\Delta_x = \Delta_z = 5.33 \mu\text{m}$ for the second and third setups. After images are taken, MATLAB is used to process and analyze information from the images. The aspect ratio in some of the images are not always 1 : 1 and the scale bars used in the images represent the scale only for the respective dimension.

Chapter 3

Theory of Superconductor and Superconducting Vortex Traps

3.1 Introduction

Superconductivity was discovered by Kamerlingh Onnes in 1911 when the resistance of a solid mercury wire immersed in liquid helium suddenly becomes zero at 4.2 K [Onnes 1991]. Soon after, more metals and alloys are also found to display this perfect conducting behavior. In 1933, Walther Meissner and Robert Ochsenfeld noticed repelling of all the magnetic field from a superconductor while measuring magnetic field distribution of superconducting tin and lead samples [Meissner and Ochsenfeld 1933]. This perfect diamagnetism phenomenon exhibited by a superconductor is known as the Meissner effect. These two phenomena are hallmarks of superconductivity.

3.2 London Equations

In order to explain the superconducting phenomena, Fritz and Heinz London expanded Maxwell equations based on the two-fluid model used for superfluid ^4He [London and London 1935]. The first London equation and second London equation [Edwards 1981] show the relation between superconducting current density J_s and the electromagnetic field as follow

$$E = \frac{\partial}{\partial t}(\Lambda J_s) \quad (3.1)$$

$$B = -\nabla \times (\Lambda J_s) \quad (3.2)$$

where Λ is the London parameter

$$\Lambda = \frac{m^*}{n^* q^{*2}} \quad (3.3)$$

with m^* , n^* and q^* denote the mass, density and charge of the carriers.

The first equation relates the electric field E to superconducting current density J_s without the resistance term and shows the perfect conducting behavior. The second equation relates the magnetic field B to J_s and expresses perfect diamagnetism explaining the Meissner effect.

After vector transformation and equating with Maxwell equation, the second London equation can be transformed into a differential equation,

$$\nabla^2 \mathbf{B} = \frac{1}{(\lambda_L)^2} \mathbf{B} \quad (3.4)$$

For an applied magnetic field, equation 3.4 shows that the B field is decaying exponentially over a distance λ_L called London penetration depth

$$\lambda_L = \sqrt{\frac{\Lambda}{\mu_0}} = \sqrt{\frac{m^*}{\mu_0 n^* q^{*2}}} \quad (3.5)$$

The penetration depth is the distance to which screening currents penetrate into the surface of the superconductor. Since λ_L varies with n_s , λ_L is temperature dependent and found to have empirical relation [MEHTA 2008],

$$\lambda_L(T) = \frac{\lambda_L(0)}{\sqrt{1 - \left(\frac{T}{T_c}\right)^4}} \quad (3.6)$$

By equating Eq. 3.5 and Eq. 3.6, temperature dependent $n_s(T)$ can be expressed as

$$n_s(T) = n_s(0) \left[1 - \left(\frac{T}{T_c}\right)^4 \right] \quad (3.7)$$

3.3 Ginzburg-Landau Theory

In 1950, Ginzburg and Landau developed a theory of superconductors from thermodynamic aspects based on phase transition called the Ginzburg-Landau Theory [Ginzburg and Landau 1950, Ginzburg 1955]. The basic formalism of the theory is defining the complex order parameter superconducting wavefunction $\psi(r)$ that relates the spatial dependent superconducting charge density $n_s^*(r)$ by the equation,

$$\psi^*(r)\psi(r) = n_s^*(r) \quad (3.8)$$

The illustration of normal and superconducting interface showing magnetic field penetration and superconducting charge density variation is shown in Fig. 3.1.

Figure 3.1: Illustration of normal (N) and superconducting (S) interface showing magnetic field (B) penetration and superconducting charge density n_s variation where λ is penetration depth, ξ is coherence length and ψ_∞ is a fully ordered superconducting state.

The thermodynamic free energy at superconducting state $F_s(r)$ is introduced with expansion of $\psi(r)$,

$$F_s(r) = F_n + \alpha|\psi|^2 + \frac{1}{2}\beta|\psi|^4 + \frac{1}{2m^*} [(-\hbar i \nabla - q^* \mathbf{A})\psi]^2 + \frac{B^2}{2\mu_0} \quad (3.9)$$

where F_n is thermodynamic free energy at normal state, α and β are expansion parameters, $\mathbf{A}$ is magnetic field vector potential. β is positive and the sign of α depends on temperature.

At zero external field and neglecting kinetic term, by minimizing the free energy with respect to ψ , the equation can be written as

$$\psi(\alpha + \beta|\psi(r)|^2) = 0 \quad (3.10)$$

The equation has two solutions $\psi = 0$ for $T > T_c$ (non-order: normal) and for $T < T_c$ (order: superconducting) the equation is simplified to

$$|\psi(r)|^2 = \frac{|\alpha|}{\beta} \quad (3.11)$$

By substituting the parameters, the free energy becomes

$$F_s - F_n = -\frac{\alpha^2}{2\beta} \quad (3.12)$$

Free energy minimization takes place via thermodynamic critical field B_c , and for the superconductor,

$$F_s - F_n = -\frac{\alpha^2}{2\beta} = -\frac{B_c^2}{2\mu_0} \quad (3.13)$$

From this equation, the expansion parameters are linked with physical quantity B_c . Since α is temperature dependent term, critical field B_c is

$$B_c = \left[\frac{\mu_0 \alpha(T)^2}{\beta} \right]^{1/2} = B_c(0) \left[1 - \left(\frac{T}{T_c} \right)^2 \right] \quad (3.14)$$

where T/T_c is the reduced temperature and the relation is experimentally observed [Tešanović et al. 1992].

By taking the kinetic energy term into account in 1D at no external magnetic field and minimizing the free energy, the equation can be written as

$$\alpha\psi + \beta|\psi(r)|^3 - \frac{\hbar^2}{2m^*} \frac{d^2}{dx^2} \psi = 0 \quad (3.15)$$

In normal to the superconducting interface, spatial variation of ψ is

$$\psi(r) = \psi_\infty f \quad (3.16)$$

where ψ_∞ is a fully ordered state and f is some parameter. The equation in terms of f become

$$\alpha f + \beta f^3 - \frac{\hbar^2}{2m^*} \frac{d^2}{dx^2} f = 0 \quad (3.17)$$

By considering very small variation length and neglecting f^3 , a parameter called coherence length ξ is extracted from the equation,

$$\xi^2 = \frac{\hbar^2}{2m^*|\alpha(T)|} \quad (3.18)$$

ξ is a length scale the superconducting wavefunction approaches to the fully ordered state from the normal state at the interface. By using Eq. 3.12 and 3.13, ξ becomes

$$\xi = \xi(0)(1 - \frac{T}{T_c})^{-1/2} \quad (3.19)$$

where,

$$\xi_0^2 = \frac{2\pi n_s^* \hbar^2}{m^* B_c^2} \quad (3.20)$$

The London penetration depth λ_L can also be derived from Ginzburg-Landau formalism, and has the same form as Eq. 3.5¹.

$$\lambda_L(T) = \sqrt{\frac{m^*}{\mu_0 q^{*2} |\psi(T)|^2}} = \sqrt{\frac{m^*}{\mu_0 q^{*2} n_s^*(T)}} \quad (3.21)$$

[Microscopic BCS superconductivity theory showed that the superconducting charge carriers are Cooper pairs (two electrons bound together below superconducting transition temperature)] [Cooper 1956a]. Thus, $m^* = 2m_e$, $q^* = 2e$ and $n_s^* = n_s/2$. m_e , e and n_s are mass of the electron, elementary charge and the density of the superconducting electrons.

The important parameter from this formalism that can explain two types of superconductors that behave differently is the ratio of $\lambda_L(T)$ and $\xi(T)$ called the Ginzburg-Landau Parameter κ ,

$$\kappa = \frac{\lambda_L(T)}{\xi(T)} \quad (3.22)$$

It is approximately constant and independent of temperature. Ginzburg-Landau theory characterizes a superconductor that has the ratio of $\kappa < 1/\sqrt{2}$ for a type-I superconductor and $\kappa > 1/\sqrt{2}$ for a type-II superconductor.

For type-I superconductor, when the temperature of the superconductor is varied from above T_c to below T_c , the state transits from normal conducting to superconducting. For type-II superconductor, at a temperature below T_c and for an applied magnetic field B_{ext} lower than B_{c1} (lower critical field), it displays the same Meissner behavior as a type-I superconductor. Based on Ginzburg-Landau formalism, B_{c1} is written as

¹ n_s^* is used in this Sec. 3.3 instead of n^* in previous Sec.3.2 to emphasize on superconducting charge density

$$B_{c1} = \frac{\phi_0}{4\pi\lambda(T)^2} \ln \kappa \quad (3.23)$$

However, when the B_{ext} is raised above B_{c1} but falls below B_{c2} (upper critical field), it transits from the Meissner state to the mixed state (vortex state). At the mixed state, there are fields penetrating into the superconductor in the form of vortices (Abrikosov vortices) where every single vortex has a unit of single flux quantum $\phi_0 = h/2e$. Thus, the mixed state is a superconducting state which has a mixture of a superconducting (vortex free region) region and a normal conducting region (vortex region). If the superconductor has a few or no defects, the Abrikosov vortices will enter from the edges of a superconductor. Due to interaction among vortices, they will arrange themselves in a triangular lattice. When defects are present, the vortices will be pinned to the defects and remain there because it is energetically more stable at these sites [Braginski and Clarke 2004]. A further increase of B_{ext} will result in decreasing distance between the vortices. If the applied magnetic field is above B_{c2} , the superconductor becomes normal conducting. This occurs when the distance between vortex is equal to the vortex core size ξ , thus deriving the formula for B_{c2} as

$$B_{c2} = \frac{\phi_0}{2\pi\xi(T)^2} \quad (3.24)$$

3.4 Critical State Models of Vortex Distribution

Type-II superconductors allow formation of vortices inside the superconductors in mixed state when an external magnetic field is applied for $B_{c1} < B_{ext} < B_{c2}$. When $B_{ext} \ll B_{c2}$, and temperature is close to T_c , penetration of vortices is more uniform. The collective behavior of vortices can be treated as supercurrent flowing in superconductors described in critical current models [Bean 1964, Brandt 1996a]. The Bean model assumes the field penetrated region is at its critical current value. The Brandt model takes into account spatial variation of the critical current density to improve further.

The Bean model is used for the qualitative behavior of the supercurrents of our superconductor. The numerical simulations presented are done using the Brandt model for more accurate description. Type-II superconductors usually have some defects and serve as pinning centers for the vortices. During the application of B_{ext} , an equilibrium phase is established between the pinning and mutual repulsion of vortices due to the Lorentz force. After B_{ext} is reduced to zero, a new equilibrium phase called the remanent state is established among the remaining vortices.

3.4.1 Supercurrent from External Field Pulse

In our model, $B_{ext} \ll B_{c2}$ and magnetic field direction is perpendicular to the surface of the thin type-II superconducting structures. From the Bean model, the region where the flux penetrates will have a critical current density J_s . Since the thickness of superconducting structures (800 nm) is much smaller compared to the width and the length of the structures in our thin film atom chip, the sheet current density is defined as $J(x) = j(x)d$ with $j(x)$ being the local current density and d is the thickness of the structures.

The sheet current density $J(x, B_{ext}, J_c)$ is given by [Brandt 1996b, Zhang et al. 2010b],

$$J(x, B_{ext}, J_c) = \begin{cases} \frac{2J_c}{\pi} \tan^{-1} \left[\frac{x}{w} \sqrt{\frac{w^2 - b^2}{b^2 - x^2}} \right] & \text{if } |x| \leq b \\ J_c \frac{x}{|x|} & \text{if } b \leq |x| \leq w; \end{cases} \quad (3.25)$$

where J_c is the critical sheet current density with $J_c = j_c d$, w is half of the width of superconductor and b is the flux free region with

$$b = \frac{w}{\cosh \frac{B_{ext}}{B_c}} \quad (3.26)$$

And B_c is the thermodynamic critical field from G-L theory and can be expressed as

$$B_c = \frac{\mu_0 J_c}{\pi} \quad (3.27)$$

The maximum penetration field can be derived using Eq. 3.26 with $b = 0$,

$$B_p = \frac{\mu_0 j_c d}{\pi} \ln \frac{2w}{d} \quad (3.28)$$

A schematic diagram in Fig. 3.2 shows the physical parameters of a model superconductor and direction of applied magnetic field. The illustration of a vortex current I induced by an external magnetic field pulse B_{ext} inside a superconducting square structure is shown in Fig. 3.3.

3.4.2 Distribution of Supercurrent and Remanent Magnetic Field

When magnetic field pulses are applied to superconductors, the rising edge of the applied field B_{ext} induces vortices while the falling edge induces anti-vortices from the superconducting edge. Vortices and anti-vortices are essentially current loops and the magnetic field direction of anti-vortices points in the opposite of

Figure 3.2: Physical parameters of the superconducting slit used for sheet current model where (w) and (d) are the width and the thickness of the slit with square pulse of B_{ext} applied to the superconducting slit.

vortices. When B_{ext} decreases to its final value B_f and $-B_{ext} < B_f < B_{ext}$, the total current density can be expressed as [Brandt 1996b],

$$J_{total} = J(x, B_{ext}, J_c) - J(x, B_{ext} - B_f, 2J_c) \quad (3.29)$$

According to this model, the time duration between the rising and falling of the field does not affect J_{total} . The distribution of J_{total} also does not depend on the patterns of the rising and falling field.

Fig. 3.4 shows the remanent current density distribution of the critical state model for $B_{ext} = 0$ to B_{max} to 0. The black line is given by the rising edge of the magnetic pulse and the red line is from the falling edge of the pulse. The total remanent current density is represented by a blue line. If the direction of B_{ext} is inverted the current distribution is reversed at $x = 0$. The contribution of the currents from vortices free region is very small. The currents from superconducting vortices mostly concentrate in the flux penetration region of $x > b$. The current distribution from a magnetic field pulse can be estimated to a pair of supercurrents with the same magnitude flowing in the opposite direction at the outer region $x > b$ of the superconducting structure.

3.4.3 Magnetic Traps from Remanent Field

The cold atoms can be trapped in a magnetic field minimum. Bias fields are used to generate a field minimum by adding or canceling the magnetic field created by

Figure 3.3: Illustration of a vortex current I induced by an external magnetic field pulse B_{ext} inside a superconducting square structure. Bias fields can be applied to the superconducting square that has been magnetized with B_{ext} to form magnetic traps for cold atoms.

Figure 3.4: Simulations of remanent current for external magnetic field pulse of $B_{ext} = 0$ to B_{max} to 0 with $B_{max} = 2B_c$, $2.4B_c$ and $3B_c$ from left to right. Black line: sheet current density for $B_{ext} = 0$ to B_{max} ; Red line: sheet current density for $B_{ext} = B_{max}$ to 0; Blue line: final remanent sheet current density.

remanent current from the superconducting vortices. In order to generate confinement in both x and y - directions, superconducting structures can be designed as a Z-shape or a U-shape structure. Examples of simulations of the different magnetic traps formed by using different bias fields are shown in Fig. 3.5. Various trapping potentials can be created by using different trapping geometries and varying the magnetic field pulses in magnitude, direction, and sequential order as described in the paper [Zhang et al. 2010b].

Fig. 3.5 shows the contour plot of the absolute magnetic field simulated using $B_{ext} = 0$ to $2.4B_c$ to 0 with bias fields. The superconducting current distribution of $B_{ext} = 0$ to $2.4B_c$ to 0 is shown in Fig. 3.4. A single trap can be formed at the side of the structures using the bias field $B_x^{bias} = 0.173B_c$ as shown in Fig. 3.5.a). The trap distance from the surface is $0.8w$ in this case and it can be vary by changing the magnitude of the bias field. The trap can be shifted to the center of the structure by applying a bias field in z -direction $B_{bias}^z = 0.2B_c$ as shown in 3.5.b). The trap to surface distance is $1w$ in this case and it can also be changed by varying the strength of B_{bias}^z .

Figure 3.5: Simulations of magnetic trap using $B_{ext} = 0$ to $2.4B_c$ to 0 a) A single trap formed at the edge of the structure with $B_x^{bias} = 0.173B_c$ b) A single trap formed above the centre of the structure with $B_z^{bias} = 0.2B_c$. Picture adapted from [Zhang et al. 2010b]

Various trapping potentials can be created by varying the geometries of the superconducting patterns. A disk shaped superconducting film can create a self-sufficient trapping potential without external bias field as shown in Fig. 3.6 [Zhang et al. 2012b]. A ring shaped potential can be created by a ring shaped superconducting pattern as shown in Fig. 3.7 [Zhang et al. 2012b].

Figure 3.6: Simulations of magnetic trap using two loading pulses of $B_{ext} = 0.8 B_c$ and $B_{ext} = -0.4 B_c$ on a superconducting disk structure. A self-sufficient trap is formed above the disk center. The field variation per contour line is $9.5 \times 10^{-4} B_c$ [Zhang et al. 2012b].

Figure 3.7: Simulations of magnetic trap using loading pulses of $B_{ext} = 0$ to $1.2 B_c$ to $-0.6 B_c$ to 0 on a superconducting ring structure using bias field $0.06 B_c$. A ring trap is formed above the ring structure. The field variation per contour line is $1.2 \times 10^{-3} B_c$ [Zhang et al. 2012b].

3.5 Discussion

In this chapter, we have gone through theoretical background of superconductors and critical current models for remanent magnetic field distribution in type II superconductors. We have discussed magnetic trapping potentials for ultra-cold atoms using the remanent field of type-II superconductors. In our previous experiments, the numerical simulations of magnetic field potentials for different superconducting structures and various magnetic potentials including double trapping potentials and ring potentials are studied [Zhang et al. 2012b]. Our previous experiments demonstrated that trapping potentials can be transformed from one type to another by varying the directions and strength of homogeneous bias field. Thus, we have shown the versatility and reconfigurability of vortex based magnetic traps in type-II superconductors. In addition, a ring potential can be generated in superconducting structures by optically manipulating the superconducting vortices and can be used for on-chip atom interferometry applications [Wu, Su, and Prentiss 2007, Gustavson, Landragin, and Kasevich 2000]. From an alternative perspective, the trapped atoms can be used as a probe for magnetic field from the vortices inside the superconductor. We will discuss experimental realization of these concepts in the following chapters.

Chapter 4

Superconducting Square Trap for Cold Atoms

4.1 Introduction

Since their first demonstration in 2000 [Dekker et al. 2000], atom chips have been predicted to revolutionize matter wave physics. Atoms can be coherently controlled by using microscopic patterns on atoms chips for matter wave physics applications. In our atom chip, arbitrary patterns of superconducting structures can be created by optically manipulating the vortices on the superconducting square structure. This chapter describes our superconducting square structure and probing of trapping potentials for square structure using ultracold atoms. The next Chapter 5 presents the designing of tailored potentials using superconducting vortex patterns and respective applications.

4.2 Superconducting Square Trap Experiment

In our superconducting atom chip experiment, ultracold atoms of ^{87}Rb are prepared with a standard laser cooling and trapping technique before being transferred to the magnetic trap. The details of these procedures were discussed in Sec. 2.8. The field gradient of the lower magnetic trap can be varied from 20 to 35 G/cm. The magnetic field B_{ext} induced on the surface of the chip due to the field gradient is 69 to 121 G since chip surface is 35 mm from the trap. The magnetic fields induced are above the first critical field $B_{c1} \approx 25$ G but below the second critical field B_{c2} of our YBCO type-II superconductor and the magnetic field from the lower trap can be used to induce vortices in the superconducting structures.

If $B_{ext} > B_{c1}$, magnetic flux penetrates through the superconductor, vortices are induced and remain pinned in the superconductor. These vortices can be used for trapping the atoms near the surface of the chip as discussed in Sec. 3.4.3. Atoms from the lower magnetic trap are transferred to the upper magnetic trap and then to the superconducting vortex trap. Since the magnetic field used for

the upper magnetic trap is lower than the lower trap, the superconductor retains the memory of the higher magnetic field generated by the lower trap.

4.2.1 Superconducting Square Trap

The optical manipulation of superconducting vortices is carried out in the $1 \times 1 \text{ mm}^2$ square structure. Superconducting vortex distribution in a superconductor can be modelled as vortex currents running at the edge of the superconductors as discussed in Sec. 3.4.2. And the vortex currents induced in the superconducting square structure is illustrated in Fig. 3.3. A plot of the trapping time with the corresponding number of atoms of the square trap is shown in Fig. 4.1. The lifetime extracted from an exponential fit to the curve is about 6 s.

Figure 4.1: Plot of the atom number in the square trap with corresponding trapping time (blue) with a fitted exponential curve (red). The fitted lifetime is ~ 6 s.

In order to configure the vortex current to achieve desired traps such as a ring trap for ultracold atoms, vortices in the superconducting square are manipulated optically in our experiments. Superconducting atoms can be used as a probe to test changes in the magnetic field potential resulting from a modified vortex structure. In the following sections, probing of the magnetic field potential is carried out for the square superconducting structure without optical manipulation. In Chapter 5, simple patterns of laser light such as a line is used to illuminate onto the square to transform the square into two rectangles and the resulting magnetic field potentials probed by cold atoms is discussed.

Figure 4.2: Vortex Distribution Imaged with Magneto Optical Imaging. a) Superconducting vortices in a Nb thin film with $B = 70 \mu\text{T}$. b) Superconducting vortex lattice in NbSe_2 crystal with $B = 0.2 \text{ mT}$. Picture adapted from [Goa et al. 2003]

4.3 Probing Magnetic Field of Vortices with Ultracold Atoms

Magneto-Optical Imaging (MOI) is typically used for studying vortex distributions in a superconductor. A magnetic thin film is placed on top of the superconductor and distribution of vortices is imaged from detecting the rotation of the light polarization induced by magnetic field. It is best suitable for determining location and density of the vortices. The vortex distribution from a typical MOI is shown in Fig. 4.2. However, the resolution of this imaging decreases with the distance from the surface of the superconductor and the requirement of magnetic thin film prohibits the probing of the magnetic potentials in our atom chip experiment. On the other hand, cold atoms can be used to probe active magnetic field distribution from superconducting structures. This section describes how ultracold atoms are used to probe the magnetic distribution of vortices from superconducting structures.

When cold atoms are prepared in the low field seeking state, they are attracted towards the magnetic field minima of the vortex traps. By varying the bias field, the minima are shifted accordingly and the atoms follow the new minima. From the absorption images, the magnetic field distribution of vortices can be reconstructed. Most of all, probing the magnetic field distribution gives a better understanding of our theoretical critical state model discussed in Sec. 3.4 and serves as a tool for engineering complex vortex potentials.

4.3.1 Magnetic Field Distribution Perpendicular to Surface

The trap minimum is formed at the point in which the magnetic field from vortices cancels out the bias field. In order to scan the perpendicular magnetic field distribution in superconducting square, the perpendicular bias field is increased

Figure 4.3: Absorption images of atoms with increasing bias field (18G, 28G, 38G, 42G) in perpendicular to superconducting square surface (illustrated with the dashed line). The upper cloud is a reflection from the chip surface. The two clouds are getting closer with increase in bias field as the cloud moves closer towards the surface.

and absorption images of atoms are captured in each step. The bias field is increased significantly to capture noticeable displacement of atom cloud up to the maximum of 42 G. Four different absorption images of atom cloud are shown in Fig. 4.3. It is found that the trap minima moved up as the bias field is increased. This shows that the vortex fields are stronger as it is closer to the chip surface as expected from the magnetic field originated from the vortices on the surface of the superconducting structure. The distance of the atomic cloud measured from the chip surface with respect to the magnetic field is plotted in Fig. 4.4.

4.3.2 Magnetic Field Distribution Parallel to Surface

The field can also be probed in the parallel direction by varying the parallel bias field. The parallel bias field is first increased in the positive y-direction and the field minimum is found to be shifted towards the same positive y-direction. After that, the field is increased in the negative y-direction in the same steps and the minimum is shifted towards the direction of the field. The absorption images of the atom cloud movement in the positive y-direction are shown in Fig. 4.5. The graph of the cloud positions and corresponding bias fields is shown in Fig. 4.6.

From the graph 4.6 and Fig. 4.5, asymmetry in magnetic field distribution with respect to zero parallel bias field can be detected. It is found that the right part of the square produces slightly weaker magnetic field and atoms are trapped closer to the surface on the right side. The amount of imbalance in the magnetic field can be extracted from symmetry of the atom cloud. This is in the order of a few gauss depends on the applied magnetic field. This slight imbalance could be intrinsically coming from the uneven distribution of pinning centers or misalignment of the magnetic fields from the coils with respect to the surface of the superconducting structures. By probing with cold atoms we can detect this imperfection and correct accordingly with bias fields to generate symmetric trapping potentials.

Figure 4.4: Graph of position of atoms vs increasing bias field (18G, 28G, 38G, 42G) perpendicular to superconducting square surface. (The positions are measured from the surface of the chip.)

Figure 4.5: Absorption images of atoms vs increasing positive bias field (in ~ 3.55 G steps starting from 0 G) in parallel to superconducting square surface. The upper cloud is a reflection from the chip surface (illustrated with the dashed line). The two clouds are getting closer with increase in bias field as the cloud moves closer towards the surface.

Figure 4.6: Graph of atoms vs increasing bias field parallel to superconducting square surface (in ~ 3.55 G steps). The positions are measured with reference to the atom cloud position with zero bias field.

4.4 Discussion

This section discussed probing the vortex field of superconducting square with cold atoms in our experimental setting. The positions of the atomic clouds give information of the field distribution of a superconducting square trap. The probing result showed the vortex field distributions follow critical current model [Bean 1964, Brandt 1996a] discussed in Sec. 3.4. However, due to imperfection of superconducting material and vortex pinning centers, it is important to probe the vortex distribution in the experiment and optimize the trapping potential from the experimental results. As discussed in Chapter 3, the shape of trapping potentials depends on the geometry of the superconducting structure. Because of the nature of the atom chip setup in a vacuum environment, changing the new atom chip is not a feasible option when a new structure is required to produce a particular potential. The manipulation of the superconducting square structure with laser illumination is a quicker and more robust method to create desired superconducting structures and tailored trapping potentials. Due to advancement in light shaping devices such as DMD, arbitrary pattern of light can be illuminated on the superconducting structures and arbitrary trapping potential can be implemented. The details of optical manipulation of superconducting vortices are discussed in the next Chapter 5.

Chapter 5

Optically Tailored Magnetic Potentials Based On Superconducting Vortices

5.1 Introduction

In this chapter, optical manipulation of superconducting vortex structures to create tailored magnetic trapping potentials for ultracold atoms is presented. We will consider what happens to superconductors when they are exposed to laser light. The effect of laser on a superconductor film can be broken down in two parts. Firstly, cooper pairs breaking from absorption of laser light by electrons and phonons is briefly discussed in Sec. 5.2. The cooper pairs breaking and relaxation occurs only in the light penetration region at picosecond timescales. The more relevant interaction for our experiment is the heating effect of the superconducting material by the laser light. The rise in the temperature of the superconducting thin film and destruction of superconductivity and corresponding vortices from heating are analyzed in Sec. 5.3.

5.2 Optical Effect on Superconductors

American physicist Leon Cooper discovered the binding of electrons pairs at low temperature in 1956 [Cooper 1956b]. John Bardeen, Leon Cooper, and John Schrieffer later formulated BCS theory of superconductivity and showed that superconductivity is facilitated by cooper pairs [De Aquino 2012]. Cooper pairs have binding energy in the order of meV and low-intensity illumination is enough to break them up. However, optical effect is limited only to optical penetration depth δ_p . The optical depth can be linked to attenuation constant $\alpha/2$ and complex reflective index $\bar{n}$ by the equation [Jackson 1999],

$$\frac{1}{2\delta_p} = \frac{\alpha}{2} = \frac{2\pi}{\lambda} \text{Im}(\bar{n}) \quad (5.1)$$

where λ is wavelength of the laser and $Im(\bar{n})$ is imaginary part of the complex refractive index. With the heating laser wavelength of 1064 nm and $Im(\bar{n})$ of 0.403 for ($T_c \sim 87\text{ K}$) [Kezuka et al. 1991], the optical penetration depth is estimated to be about 200 nm for our YBCO sample. Since the YBCO sample has thickness of 800 nm , this optical effect only accounts for a fraction of the whole film. Another mechanism is required for effective manipulation of superconducting vortices in our YBCO film.

5.3 Laser Heating Effect on Superconductors

Superconductivity and superconducting vortices can be destroyed by heating up the surface only by a few degrees [Testardi 1971a] due to thermal stress. Because of the relatively thick layer of our YBCO superconducting film, the thermal effect is the primary factor in manipulating superconducting vortices in our case. The effect of laser heating on a superconductor can be broken down into two parts, the rise in surface temperature due to initial heat absorption on the illuminated area and heat diffusion in other parts of the material. The spreading of heat, in turn, affects the superconductivity and corresponding vortices in a vicinity of the light absorption area. The laser pulse time and power output are precisely adjusted to create desired vortex patterns on the superconducting film.

Figure 5.1: Illustration of surface heating by laser light. The atom chip has a 800 nm layer of YBCO on top of the YSZ substrate.

5.3.1 Heat Absorption and Temperature Rise

For the laser pulse in order of milliseconds, the interactions of microscopic electron-phonon are insignificant and increase in surface temperature by the laser can be described by a heat diffusion equation [Lin 1999] to analyze the surface temperature rise of YBCO in the illuminated area as shown in Fig. 5.1,

$$T(t_p) - T_0 = \int_0^{t_p} \frac{F_d(t)dt}{\sqrt{\pi K C_v (t_p - t)}} \quad (5.2)$$

where F_d is power flux deposited into the material, K is thermal conductivity, ρ is density and C_v is heat capacity of the material. T_0 is initial temperature, $T(t_p)$ is the temperature after pulse length t_p .

It is important to determine the surface temperature in order to avoid the melting of the superconducting coating. YBCO has melting temperature ≈ 1040 K [Tair et al. 2017]. Although this high melting temperature prevents permanent destruction of superconductivity for low temperature rise, it is still possible to damage the material with tightly focused high power beam. For this reason, only moderate power outputs (*ms* pulses and up to about 1 W power outputs) are used in all the experiments.

For square pulses, the surface temperature rise $T(t_p)$ is given by

$$T(t_p) - T_0 = F_d \frac{2\sqrt{t_p}}{\sqrt{\pi K \rho C_v}} \quad (5.3)$$

with F_d is the power flux and $T(t_p)$ is temperature rise as square root of the pulse time ($\sqrt{t_p}$) which describes a generic characteristic of heat diffusion. Throughout the experiment square pulses of different pulse times are used to breakdown the superconductivity and manipulate the superconducting vortices.

The power deposited into the materials can be determined from the reflectance of the material for thin films. When shining a laser perpendicularly onto a material surface, the reflection coefficient can be described as

$$r = \frac{n - 1}{n + 1} \quad (5.4)$$

where $n = \sqrt{\epsilon}$ is the refractive index. For infrared region, Drude model gives adequate result [Clark, White, and Machiels 1986] with

$$\epsilon = 1 - \frac{w_p^2}{w^2 + iww_T} \quad (5.5)$$

where w_p^2 and w_T are plasma and collision frequency respectively. From energy conservation, the flux deposited into the material is given by

$$F_d = (1 - |r|^2)I_0 = (1 - R)I_0 \quad (5.6)$$

with R is reflectance of material and I_0 is the incident laser irradiance.

In all of our calculations thus far, we have assumed that reflection of the laser energy occurs entirely at the surface. As for the thickness of a thin film which is in the order of laser penetration length, the transmittance also has to be considered in order to get the effective power flux absorbed by the material.

Figure 5.2: Graph of surface temperature rise vs laser pulse time for an absorption power of 100 mW on YBCO square structure of 1 mm².

The rise in surface temperature of 1 mm² YBCO structure for an absorption power of 100 mW in different laser pulse times is shown in Fig. 5.2. A YBCO thin film has an average reflectance of about 10% [Chen 2005]. Therefore, the absorption power flux is $\sim 90\%$ of incident power flux. In our experiment, the power flux measured is the incident power flux and all the calculations are based on the incident power flux if they are not stated otherwise.

In order to verify the diffusive temperature model 5.3 for the rise in temperature and destruction of superconductivity by laser heating, data from paper by Testardi were used [Testardi 1971a]. Table 5.1 shows two different light pulses used for destroying superconductivity of T_c for Pb thin film.

For lead thin film at superconducting temperature with thermal conductivity of 0.358 W/cm * K [De Haas and Rademakers 1940], heat capacity of 0.0312 cal/mol * K [Horowitz et al. 1952] and density of 11.34 g/cm³, using Eq. 5.3, temperature rise ΔT is 0.42 K and 0.93 K for 40 μ s (3 W/cm²) and 6 μ s (17 W/cm²) pulse respectively. Due to the finite thickness and approximation errors of low temperature thermal parameters of lead, the values deviate about 10%. The deviation is

Laser light and heating magnitudes and T_c reduction				
Laser Pulse Width (μs)	Absorbed Power (W)	Absorbed Power/Area (W/cm^2)	Observed Heating (K)	T_c Reduction Full Power (K)
40	0.3	3	0.45	3.2
6	0.75	17	1	6

Table 5.1: Destruction of superconductivity with laser light, illustrating rise in temperature and reduction of superconducting transition temperature T_c . Table adapted from the paper by [Testardi 1971b].

within the acceptable range and the equation 5.3 gives adequate result for surface temperature rise for the pulsed laser heating.

The other important heating effect presented in table 5.1 is a reduction of superconducting transition temperature due to formation of resistive state by increase in energy of the electron gas from the absorption of the laser beam [Testardi 1971a]. The photo-induced resistive state is only found in the length scale of comparable to or less than the optical penetration depth and the superconducting coherence length. Since this resistive state length is a fraction of the thickness of our YBCO film, the reduction effect is not significant and the original critical temperature of our film is considered for destroying superconductivity and manipulating the superconducting vortices.

5.3.2 Laser Heating Effect on YBCO Z-shaped Structure

Our YBCO film has a critical temperature of 87 K. The power flux and pulse time of the laser were analyzed to obtain the required parameters for heating up the superconducting YBCO to the normal state. In order to determine the transition, $3\text{ mm} \pm 2\%$ circular light spot is illuminated for 200 ms on the Z-shape structure of our superconducting atom chip. The resistance is calculated from the voltage drop of 10 μA current running through the superconducting structure. The resistance values are plotted with respect to the power as shown in Fig. 5.3.

The resistance value starts to rise from zero at the incident laser power of $\sim 390\text{ mW}$ as shown in Fig. 5.3. Since our film is thicker than the optical depth of YBCO, only loss from reflection of 10% [Chen 2005] is considered. The power deposited on the YBCO structure is $\sim 351\text{ mW}$ for $\sim 390\text{ mW}$ of incident power. The light spot has radius of 1.5 mm and the absorption power flux is 49.65 mW/mm^2 . YBCO has a density of 6300 kg/m^3 , average heat capacity of about $123.8\text{ J/kg} \cdot K$ [Shaviv et al. 1990] and average thermal conductivity k_{avg} of $8.5\text{ W/m} \cdot K$ [Pu 1999] around 77 K.

From equation 5.3, the temperature rise is calculated to be $\sim 9.73\text{ K} \pm 4\%$ for 200 ms pulse. The initial temperature of YBCO is at the liquid nitrogen temperature 77 K and the temperature becomes YBCO is $86.73\text{ K} \pm 4\%$ after laser heating.

Figure 5.3: Graph of power vs resistance for laser exposure of 200 ms on a Z-shaped superconducting structure.

The result agrees well with our YBCO the critical temperature of 87 K within the acceptable margin of error.

5.3.3 Laser Heating Effect on YBCO Square Structure

We have investigated the heating effect and transition temperature on a superconducting Z-shape structure from change in resistivity. However, in order to optically manipulate vortex structure, the most suitable superconducting structure is the square structure on our atom chip. Since there is not enough electrical connection attached to square structure, we cannot measure resistivity and thus, cold atoms are used to probe the heating effect and transition temperature of the square.

First of all, cold atoms are trapped by the vortex currents of the square superconducting structure of 1 mm^2 . After that, the rectangular laser light from the DMD is illuminated on one half of the square. Absorption images of atom cloud are taken after the laser exposure with varying laser power and exposure time. The laser exposure time and corresponding atom cloud radii are plotted in Fig. 5.4 for various incident power. The cloud radius is a good indicator of the magnetic field trapping potential that shows the geometry of source of magnetic field.

From the graph 5.4, it is clear that the radius of the atom cloud is reduced more than half of the initial value immediately for illumination of laser power of 30

Figure 5.4: Graph of radius of atom cloud vs laser exposure time for 20 to 80 mW laser light shone on half of the 1 mm^2 YBCO square.

Figure 5.5: Graph of radius of atom cloud vs laser power for 40 ms expose time due to laser light shone on half of the 1 mm^2 YBCO square.

mW onwards. As for 20 mW laser power, about 100 ms pulse length is required to reduce the cloud radius to half of its initial value, with gradual reduction in cloud radius with increasing pulse times. In order to examine this behavior, the rise in temperature for 100 ms exposure is calculated. Considering the loss of 10% from reflection as mentioned, the absorption power is calculated to be 18 mW for 0.5 mm^2 of laser illumination which gives power flux of 36 mW/mm^2 . For 100 ms of exposure, according to equation 5.3, the rise in temperature is calculated to be $\sim 4.98\text{ K}$.

The YBCO structure temperature is $\sim 82\text{ K}$ with 4.98 K rise from the heating. This temperature is still below the critical temperature of our YBCO. However, the critical current density of the superconducting YBCO vortices drops sharply in the transition region starting from 80 K as shown in the Fig. 5.6. As a result, the magnetic field from reduced vortex currents are not enough for providing the magnetic potentials needed to trap the cold atoms. This explains about significant drops in radius of the atomic cloud for 20 mW (100 ms) pulse as shown in Fig. 5.4.

Figure 5.6: Graph of YBCO critical current density vs temperature showing reduction of critical current density near superconducting transition temperature for different samples. Graph adapted from [Antoja Leonart 2014].

This characterization provides good base parameters of the power flux and timescale to manipulate the superconductivity and superconducting vortices of YBCO superconductor. However, the radius of the cloud decreases even before 100 ms and for exposure of more than 100 ms for 20 mW power, the radius of the atom cloud is reduced further as shown in Fig. 5.4. This shows that the heat from the laser is not localized and spreads to the surrounding. The decrease in atomic cloud

Figure 5.7: Graph of atoms number vs laser pulse time for 20 to 80 mW laser light shone on half of the 1 mm^2 YBCO square and half without laser illumination.

radius with increasing power for 40 ms exposure (extracted from data shown in Fig. 5.4) is shown in Fig. 5.5.

The number of trapped atoms vs laser exposure time is also plotted for various power in Fig. 5.7. The continuous decrease in the atom number for longer heating times indicates a higher rise in temperature as described by the heat diffusion equation 5.2. The spreading of heat through heat conduction in superconductor accounts for this behavior. In order to effectively manipulate only targeted vortices, heating diffusion has to be considered carefully. It is critical to analyze the heat spread in order to effectively and precisely manipulate the vortex matter for atom trapping. In the next Sec. 5.3.4, simulations of heat diffusion are carried out to account for heat spread in our experiments.

We aim to completely destroy the superconducting vortices in the laser illuminated area in order to prevent the unwanted magnetic field distributions for designing the tailored trapping potentials. Hence, the temperature of the illuminated area is needed to rise above transition temperature of 87 K. The simulations are carried out to achieve 87 K temperature in laser heating area with as less heat spread as possible to the surroundings. The heat spread is intended to keep below 80 K to prevent reduction of the critical current in desired superconducting patterns. The simulations are aimed to prove that the laser can heat up the desired area to 87 K while reducing the spread of heat to the surroundings and keeping the surrounding temperature below 80 K. Our simulations are carried

out with COMSOL multi-physics software using finite element method using the time dependent equation,

$$\rho C_p \frac{\partial T}{\partial t} + \Delta \cdot q = Q + Q_{ted} \quad (5.7)$$

where ρ is density, C_p is average heat capacity, q is input heat flux (W/m^2), Q is volumetric heat energy (W/m^3) and Q_{ted} is thermoelastic damping parameter. The heat conduction is described by $q = -k\nabla T$ with k being thermal conductivity.

5.3.4 Heat Diffusion in Superconducting Square

After characterizing the rise in temperature needed to breakdown the superconductivity and the vortices, the spreading of heat due to input heat flux is studied in this section. The simulations are carried out to heat up the illuminated area to the superconducting transition temperature of our YBCO (87 K). From simulations, the diffusion of heat from illuminated area to the surrounding is also analyzed for different pulse time on superconducting square. The effect of heat diffusion is studied for designing and manipulating the vortex traps with optical illumination in the next Sec. 5.4.

Figure 5.8: Simulation of heat diffusion due to laser illumination on one half of the superconducting square for 5 ms and the corresponding cross section (dashed line) temperature profile of the whole square.

Fig. 5.8 shows the heat diffusion due to laser illumination on one half of the superconducting square for 5 ms and the corresponding cross section temperature profile of the whole square. A significant amount of heat is spread to the surrounding from the illuminated area as shown in the temperature profile. The lowest temperature of the square is 79.3 K and the temperature of almost the whole square is 80 K. The laser exposure time plays a significant role in spreading the heat and a shorter laser pulse is needed to prevent the temperature rise of

the surrounding area below 80 K.

Figure 5.9: Simulation of heat diffusion due to laser illumination on one half of the superconducting square for 100 μ s and the corresponding cross section (dashed line) temperature profile of the whole square.

Fig. 5.9 shows a simulation of heat diffusion due to laser illumination on one half of the superconducting square for 100 μ s and the corresponding cross section temperature profile of the whole square. As described by equation 5.3, a higher laser power was needed to heat up the structure to 87 K. The lowest temperature of the square is 77 K and the heat spread only 100 μ m from the illuminated area.

The temperature of 80 K and above only spread to $50\ \mu\text{m}$. This shows that the heat spread can be controlled by adjusting the laser pulse time and using shorter pulse exposure to reduce the heat spread to less than $50\ \mu\text{m}$.

Figure 5.10: Simulation of heat diffusion due to cross pattern laser illumination on the center of the superconducting square for 1 ms and the corresponding cross section (dashed line) temperature profile cut across $y = 250\ \mu\text{m}$ above the bottom.

A single atomic cloud can be split into four clouds with a cross pattern laser light dividing the square into four different squares. The heat spread analysis is carried out for the light cutting across the square to understand the spreading of

heat for the laser pattern shone in the center of the superconducting square. Fig. 5.10 shows a simulation of heat diffusion due to a cross pattern laser illumination on the center of the superconducting square for 1 *ms* and the corresponding cross section temperature profile of the whole square cut across $y = 250 \mu m$ above the bottom. The heat seems to accumulate at the corner of the crossing of the horizontal and vertical strips. The temperature of a significant portion of the square is above 80 K and shorter laser pulse is required to reduce the heat spread for this pattern.

Figure 5.11: Simulation of heat diffusion due to cross pattern laser illumination on the center of the superconducting square for $100 \mu s$ and the corresponding cross section (dashed line) temperature profile cut across $y = 250 \mu m$ above the bottom.

Fig. 5.11 shows a simulation of heat diffusion due to a cross pattern laser illumination on the center of the superconducting square for $100 \mu s$ and the corresponding cross section temperature profile of the whole square cut across $y = 250 \mu m$ above the bottom. The accumulation of heat at the corner of the cross is scaled down to reasonable level. The temperature of the outer edge is still $77 K$ and the temperature of above $80 K$ only occurs for $50 \mu m$ from the illuminated area.

The important structure to sum up the arbitrary pattern generation of vortex matter is the ring shape pattern. In order to estimate the power needed to control the ring precisely and prevent heat spread to the surroundings, multiple simulations were carried out with different powers and pulse times. Fig. 5.12 shows a simulation of heat diffusion due to a ring pattern illumination of a $200\text{ }\mu\text{m}$ inner radius, and $100\text{ }\mu\text{m}$ thick ring onto the superconducting square for 1 ms and its corresponding cross section temperature profile. The lowest temperature of the square is 77.2 K , however, due to the enclosure of the ring, the heat is trapped inside and diffusion of heat in the center is significant and the temperature reached higher than 80 K . A shorter laser pulse is need to reduce the spreading of heat and resolve the ring structure.

Figure 5.12: Simulation of heat diffusion due to a ring pattern illumination of 200 μm inner radius 100 μm thick ring on the superconducting square for 1 ms and the corresponding cross section (dashed line) temperature profile.

As discussed previously, a shorter exposure to laser light reduces the unwanted spreading of heat. However, the temperature rise depends both on exposure time and laser power, thus higher power flux is needed to destroy the superconductivity in the illuminated area. Fig. 5.13 shows a simulation of heat diffusion due to a ring pattern illumination of 200 μm inner radius, and 100 μm thick ring onto the superconducting square for 100 μs and the corresponding cross section temperature profile. The lowest temperature is 77 K in most part of the square. The

accumulation of heat in the center is reduced significantly and the heat does not spread to the middle of the ring. The heat diffusion is reduced well and ring structure can be resolved well for $100 \mu\text{s}$ laser pulse.

Figure 5.13: Simulation of heat diffusion due to a ring pattern illumination of $200 \mu\text{m}$ inner radius $100 \mu\text{m}$ thick ring onto the superconducting square for $100 \mu\text{s}$ and the corresponding cross section (dashed line) temperature profile.

Figure 5.14: Simulation of heat diffusion due to ring pattern illumination of $200\ \mu\text{m}$ inner radius $100\ \mu\text{m}$ thick ring on the superconducting square for $1\ \mu\text{s}$ and the corresponding cross section (dashed line) temperature profile.

Further reduction of exposure time can reduce the heat spread more efficiently and shorter laser pulse of $1\ \mu\text{s}$ is simulated. Fig. 5.14 shows a simulation of heat diffusion due to a ring pattern illumination of $200\ \mu\text{m}$ inner radius, and $100\ \mu\text{m}$ thick ring onto the superconducting square for $1\ \mu\text{s}$ and its corresponding cross section temperature profile. The temperature profile shows $87\ \text{K}$ in the illuminated area and a base temperature of $77\ \text{K}$ almost everywhere in the surroundings. Thus, precise optical manipulation of ring structure can be achieved for 1

μs pulse.

Figure 5.15: Graph of heat diffusion in superconducting square due to heating of half square to 87 K temperature and corresponding diffusion length taken at 80 K temperature for various laser exposure time.

The heat diffusion to the surrounding should be kept below 80 K to prevent the reduction of vortex currents in the non-illuminated area as discussed in Sec. 5.3.3. In order to summarize the heat diffusion, the heat diffusion length to reduce the temperature of surroundings to 80 K from 87 K heat source is analyzed. Fig. 5.15 shows the heat diffusion length due to heating in an illuminated area up to 87 K, for various laser exposure times and heat diffusion length to scaled down to 80 K temperature from the heat source of 87 K temperature. The diffusion length

is relatively high for 1 ms exposure time with temperature reaching 80 K as far as 141 μm from the illuminated surface. This length is reduced significantly for exposure times of 100 μs exposure time or less. This is reduced to 3 μm for a 1 μs pulse. This result shows that short laser pulses of μs time scale are required to effectively destroy the superconductivity and manipulate superconducting vortices with desired laser illumination patterns.

However, our current laser is not capable for providing short pulses and upgrading of laser is required to operate in 1 μs pulse short pulses. The power needed for a 1 μs pulse for 200 μm inner radius and 100 μm thick ring is calculated for upgrading of our laser. The incident power flux required is 25.36 W/mm^2 and the surface area of the ring is 0.157 mm^2 , the power required is 3.98 W. Considering the 50% and 80% efficiency of the DMD and the AOM, about 10 W laser output power is required to operate in μs pulse time for effective heating to manipulate the superconducting vortices.

Due to the limitation of our laser output (1.5 W), it is not possible to heat up the YBCO structures to 87 K while containing the heat spread effectively. Instead we heat up the superconducting structures up to 82 K to significantly reduce the critical current from vortices in the illuminated area. Thus, the heat spread to the surroundings is not totally eliminated in the experiments. Even with the noise from the heat spread, we managed to get satisfactory arbitrary trapping potentials for the atoms. In next section, we used previous analysis of heat heating effect on YBCO superconducting structures to optically manipulate superconducting vortices for generating tailored magnetic trapping potentials for ultra cold atoms.

5.4 Tailored Magnetic Potentials Based on Optical Manipulation of Superconducting Vortex Structures

The designing of various tailored potentials by optically manipulating superconducting vortices on the square structure is studied in this section. The on-chip vortex distribution of superconductor is analyzed using cold atoms as a probe to characterize the vortex dynamics after the laser illumination. After the characterization, the superconducting square structure is used as a repeatable test pad to generate various superconducting patterns and geometries for creating the tailored trapping potentials. The experimental results show interchangeable arbitrary trapping potentials for ultracold atoms can be engineered with flexibility. The highlight of the experiment, realization of the ring potential using this technique, pave the way for on-chip matter wave interferometry applications.

Figure 5.16: Absorption images of atom cloud for 200 μm line of laser light cutting in the center of superconducting square with fix power and increasing exposure time from 0 to 100 ms in 20 ms step. The bias field is fixed at 28 G for all the steps and the results are due to change in vortex distribution. (The chip surface is located at the upper margin of the image frame.)

5.4.1 Manipulation of Single Vortex Trap into Two Vortex Traps

As described in Sec. 5.4.2, a single atom cloud can be transformed into two clouds by optically manipulating the vortices. A 200 μm line is illuminated on the superconducting square to destroy the vortices at the center and absorption images of atom clouds were taken to observe the effect of the laser illumination. The heat spread was observed clearly for 20 ms steps for a laser power of 60 mW. A single cloud can be split into two separate clouds with equal trapping potential as shown in Fig. 5.16. The partial split was observed for the first 20 ms and the cloud radius is reduced and split into two after 40 ms. The further heat spread was detected for 60 ms and 80 ms but the clouds are almost undetectable after 100 ms.

5.4.2 Probing Superconducting Vortex Magnetic Field with Atoms After Laser Exposure

Cold atoms are used to probe the resulting potentials of two clouds after laser light exposure in the middle of the square. One of the ways to determine distribution of vortices in a superconductor is probing the vortex density along the edges of the superconducting to normal interfaces as compared to the vortex density in the inner region of the superconducting structure. The vortices tend to enter from the edges of the superconducting structure and push towards the center. The vortex density should be denser at the edge compared to deep within the superconductor for the external magnetic field below the full penetration field as discussed in Chapter 3.

In order to probe the density, the vortices are induced in the superconducting square with $B_{\text{ext}} = 100$ G well below the full penetration field. The laser line of 200 μm is illuminated in the center of the superconducting square to divide it

Figure 5.17: Absorption images of atom cloud for 200 μm line of laser light cutting in the center of superconducting square with fix power for increasing bias field (0G, 3.5G, 10.3G, 17.4G). The upper cloud is reflection from the chip surface (dashed line).

into two rectangular structures. Each rectangular structure creates one minimum trapping potentials and a single cloud can be split into two clouds. However, the vortex density should be stronger on the outer side of the rectangles than the inner side of the rectangle. The trapping potential is modified using a bias magnetic field which is parallel to the surface and absorption images of the two clouds are taken with increasing bias field. As shown in Fig. 5.17, one of the field minima is cancelled out and one cloud disappears first. This confirms that the vortex distribution is denser on the outer side of the superconducting square as described in the critical current model in Sec. 3.4. This dynamic probing of superconducting vortex density provides an understanding of vortex distribution and gives insight for designing the superconducting vortex structures to create tailored trapping potentials.

5.4.3 Manipulation of Single Vortex Trap into Array of Vortex Traps

Figure 5.18: a) Absorption images of four atomic clouds after exposure from cross pattern laser light in the center of superconducting square. b) The corresponding DMD pattern of $200 \times 200 \mu\text{m}$ cross.

A single cloud can be split into multiple clouds with laser illumination on vortices in superconducting square. A $200 \times 200 \mu\text{m}$ cross is illuminated onto the center of

the square and absorption images of the atomic cloud were taken to observe the effect of the laser illumination. The Fig. 5.18.a) shows the absorption images of splitting of the four clouds from a single cloud after a cross pattern laser exposure shown in Fig. 5.18.b). Parts of the imaging light incident on edge of the square were lost and the two clouds in the low parts of the chip is not resolved very well. The atoms are loaded to this vortex trap from the upper magnetic trap with an atom cloud average temperature of $140\ \mu\text{K}$. Due to the shallow trapping potential, not enough atoms are trapped since the temperature of the atoms loaded to this trap is not low enough.

The atoms need to be cooled down further to the BEC stage on the atom chip in order to effectively trap and coherently manipulate them [Roux et al. 2008b]. Atoms in a BEC state can be trapped in superconducting lattices and quantum simulation operations can be performed on the atom chip. Fig. 5.19 shows illustration of laser interference patterns to manipulate vortices and create superconducting vortex lattice. Four laser beams are shone onto the superconducting square and the interference patterns from the laser light can be used to generate vortex lattices for ultracold atoms. The trap depth and lattice distance can be controlled by varying magnetic field pulses and laser patterns. The quantum simulation such as the Hubbard model can be simulated on the superconducting atom chip by utilizing the optical manipulation method.

Figure 5.19: Illustration of superconducting vortex lattices formed on superconducting square from laser interference pattern.

5.4.4 Manipulation of Vortex Structure for Generating Tailored Trapping Potential

Any arbitrary trapping potential can be created from superconducting vortices by fabricating desired vortex structures on the atom chip. However, permanent superconducting structures offer limited flexibility. Optical manipulation of superconducting vortices is extremely flexible and any arbitrary superconducting

structure can be implemented. Any design and experimental flaw can be effectively corrected with ease. Moreover, the optical manipulation method offers an ideal testing ground for generating arbitrary potentials because the superconducting vortices and superconductivity can be restored after each experimental run.

Figure 5.20: a) Absorption image of atom cloud for laser light with dot in the center and a line cut towards edge of superconducting square. b) The corresponding ring shape DMD laser light pattern.

Fig. 5.20.a) shows absorption image of ring shaped atomic cloud with a weak link tailored by the laser pattern shown in Fig. 5.20.b). The laser pattern has a dot in the center and a line cut towards an edge of the superconducting square as shown in Fig. 5.20.b). For imaging the ring-shaped atomic clouds, an imaging system with large grazing angle is set up to get rid of reflections and capture more accurate shape. This tailored ring shape potential with a weak link resembles the potential of the superconducting quantum interference device (SQUID). This novel trapping potential can be used to perform quantum interference experiments with ultracold atoms for theoretical studies as well as for implementing precision measurement devices.

5.4.5 Manipulation of Vortex Structure for On-Chip Matter Wave Interferometry Application

The matter wave interferometer can be realized by guiding ultracold atoms with micro-fabricated structures in the atom chips. Matter wave interferometers can be several orders of magnitude more sensitive compared to optical interferometers [Berman 1997]. A few experiments have been carried out with chip-based interferometer structures [Schumm et al. 2005b, Wang et al. 2005]. However, a symmetric closed Mach-Zehnder interferometer has not been realized for traditional

Figure 5.21: Calculated absolute magnetic field of the two-wire guide in the xy -plane. Picture adapted from [Müller et al. 2008b].

micro structures in the atom chips. The closed loop interferometer using two-wires guide has been proposed for on-chip interferometry [Müller et al. 2008b]. A simulation of the magnetic field distribution is shown in Fig. 5.21. This design, however, has to overcome the unwanted potential barrier created by the finite separation of two wires at the end of the circular loop.

Figure 5.22: a) Absorption image of ring shaped atomic cloud for ring laser light shone in the center of superconducting square. b) The corresponding ring shape DMD laser light pattern.

A superconducting ring vortex trap has the potential to overcome this issue due to complete enclosure of the superconducting loop. The first step to achieve the enclosed interferometer is implementing the ring potential to trap the ultracold atoms. A preliminary ring shape potential is generated by illuminating a ring pattern of light onto the superconducting square structure and using multiple external magnetic field pulses. Fig. 5.22.b) shows a DMD image of a ring with

an inner radius of $160\ \mu\text{m}$ and $120\ \mu\text{m}$ thick laser pattern used for illuminating the superconducting square. The preliminary result of corresponding absorption image of the ring shape atomic cloud is shown in Fig. 5.22.a). The thickness and radius of DMD ring patterns are simulated to study the heat diffusion and suitable parameters are used to achieve the ring potential for trapping the ultracold atoms. Further development is being carried out to improve the resolution of the ring potentials and the loading efficiency of cold atoms to the tailored potentials.

In order to improve the loading and trapping of atoms to the ring traps, the magnetic field distributions of optically manipulated superconducting vortices need to be simulated and characterized to evaluate trap depths of the vortex potentials. The main issue is the relatively shallow trap depth of the current ring potential. The atoms in the upper magnetic trap before loading to the vortex ring trap has temperature of $140\ \mu\text{K}$ and they are not cold enough to load them to the ring trap efficiently. The atoms need to be cooled down further to the BEC state to trap them in the ring potentials for a longer period and carry out interferometry operations.

Chapter 6

Conclusion and Outlook

6.1 Conclusion

We have shown ultracold atoms can be trapped and controlled by magnetic potentials from superconducting vortices. We also presented simulations and experimental results of various magnetic field potentials produced by vortices in a type-II superconductor. Utilizing the remanent field generated in the superconductor by external magnetic field pulses, we have designed various types of complex trapping geometries based on the critical state model. In the experiments, we realized single traps, double traps and an array of traps in superconducting structures. We laid out configurations of trapping potentials by varying strength and pulse times of external magnetic field B_{ext} and bias field. We have also demonstrated low-field seeking ultracold atoms can be used for probing the field distribution of the vortex structures. Magnetic field distribution of superconducting square probed by cold atoms proved the accuracy of description of the critical state model in our experiments.

In order to fully utilize the reconfigurability of vortex matter, we carried out optical manipulation on a superconducting square structure and realized tailored magnetic potentials for ultracold atoms. We set up heating laser system consisting of an infrared laser and a DMD to generate arbitrary patterns of laser light for manipulating superconducting vortices. The mapping and testing of DMD patterns to a targeted surface have been discussed. We simulated and characterized heat diffusion of light patterns on YBCO thin film using finite element method. We also pointed out high power and short laser pulse gives better results in controlling unwanted heat spreading for manipulating superconducting vortices to generate desired superconducting structures and tailored potentials. In the experiments, we successfully split a single superconducting vortex trap into two or four traps by optically patterning vortex structures in the superconducting square. The method can scale up to create superconducting vortex lattices for trapping and controlling ultracold atoms for quantum simulations and quantum computing applications [Romero-Isart et al. 2013].

We have realized a ring potential and proved the ability to generate tailored potentials by optically manipulating the superconducting vortices. We have also generated a ring potential with a weak link that resembles the SQUID potential and this potential can be used to carry out quantum interference experiments and implementing precision measurement devices. Finally, we have shown that a ring potential for interferometry can be realized with the optical manipulation method. The ring potential can be used for on-chip interferometry devices in the future [Müller et al. 2008b]. Moreover, the tailored micro-structured surface traps generated from vortices offer the unique opportunity to couple cold atoms and solid state quantum devices for quantum state transfer and information processing [Sørensen et al. 2004, André et al. 2006]. Hence, the optical manipulation of superconducting vortices shows huge potential for ultracold atoms and the applications of compact on-chip devices will draw attraction for both theoretical studies and experimental applications.

6.2 Outlook

We have discussed in the Sec. 5.3.4 that high power, short laser pulse gives better control of heat spread and effective manipulation of vortex structures. Our heating laser only has 1.5 W output power and laser pulse length of ms timescales are required to configure the superconducting vortex structures. We will upgrade the laser to a 10 W heating laser so that μs pulses can be used to effectively manipulate the superconducting vortices. The other important factor is the temperature of the atoms to be loaded to the tailored vortex traps. The cold atoms can be only cooled to $\sim 140 \mu K$ before loading into vortex traps in our experiment. Due to dimension of superconducting structures and limitation in vortex density, the traps have relatively shallow potentials. In order to effectively load and enhance the lifetime of ultracold atoms in the traps, further cooling is needed. We are setting up a RF cooling scheme to cool down atoms to $\sim 20 \mu K$ to enhance lifetime and controllability of ultracold atoms in superconducting vortex traps and move a step towards achieving BEC on our atom chip.

Once the current experimental setup is upgraded, superconducting vortices can be effectively manipulated and any arbitrary tailored potential can be realized with precise control over the parameters. Superconducting vortex lattices can be constructed on a superconducting square for quantum simulations such as Bose-Hubbard model in the future [Romero-Isart et al. 2013]. Moreover, the optically manipulated superconducting ring potential with a weak link can be designed to simulate novel trapping potential like a SQUID [Edwards 2013] for precision measurement applications. Once BEC is obtained, optically reconfigurable ring potentials will be able to carry out matter wave interferometry and lay the foundation for on-chip interferometry devices [Müller et al. 2008b].

Appendix A

Abbreviations Used for Optical and Electronic Elements

Optical and Electronic Elements	Abbreviations
Acousto-Optical Modulator	AOM
Anamorphic Prism	AP
Beam Block	BB
Dichroic Mirror	DM
External Cavity Diode Laser	ECDL
Fiber Pot	FP
Half-Wave Plate	$\lambda/2$
Quarter-Wave Plate	$\lambda/4$
Interference Filter	IF
Mirror	M
Lens	L
Lock-in Amplifier	Lock-In
Optical Isolator	OI
Piezoelectric Transducer	PZT
Photodiode	PD
Polarizing Beam Splitter	PBS
Proportional-Integral Controller	PI
Tapered Amplifier	TA
Walk-Off Polarizer	WOP

Table A.1: List of the abbreviations of optical and electronic elements used in this thesis.

Appendix B

Characterization of Magnetic Coils

Table B.1 shows power supplies used for supplying currents in the corresponding coils. All our coils have 50 windings. The currents values are measured with current meter. The computer input voltage with corresponding current and hall probe voltage for the MOT, transfer and (x,y,z) bias coils are tabulated in Table. B.2, B.3, B.4, B.5 and B.6 respectively. The relevant conversation parameters of the coils are listed in Table B.7.

Magnetic Coils	Models	Max. Voltage (V)	Max. Current (A)
MOT Coils	TDK Lambda –GEN20-165	20	165
Transfer Coils	TDK Lambda –GEN30-110	30	110
Bias Coils (x)	Agilent – 6674A	60	35
Bias Coils (y)	TDK Lambda –GEN20-76	20	76
Bias Coils (z)	TDK Lambda –GEN30-110	30	110

Table B.1: Table of the power supplies models and corresponding maximum voltage and current for supplying current in the relevant magnetic coils

Computer Analogue Voltage (V)	Measured Current (A)	Hall Probe Voltage (V)
1.00	14.3	0.16
2.00	29.6	0.328
3.00	44.6	0.492
4.00	59.7	0.656
5.00	74.9	0.832
6.00	90.2	0.992
6.50	97.8	1.08
6.75	101.6	1.13
7.00	105.4	1.17
7.25	109.2	1.21
7.50	112.9	1.24
7.75	114.4	1.25
8.00	116.6	1.28

Table B.2: MOT coils measured current and hall probe voltage v.s. computer analogue voltage.

Computer Analogue Voltage (V)	Measured Current (A)	Hall Probe Voltage (V)
1.00	8.6	0.424
2.00	17.4	0.848
3.00	26.2	1.27
4.00	35.0	1.70
5.00	43.9	2.14
6.00	52.7	2.58
7.00	61.5	3.02
8.00	70.4	3.44
9.00	79.2	3.88
10.00	88.1	4.28

Table B.3: Transfer coils measured current and hall probe voltage v.s. computer analogue voltage.

Computer Analogue Voltage (V)	Measured Current (A)	Hall Probe Voltage (V)
1.00	5.4	0.408
2.00	11.0	0.824
3.00	16.5	1.23
4.00	22.0	1.66
5.00	27.5	2.06
6.00	33.1	2.48
7.00	36.3	2.72
8.00	36.3	2.72
9.00	36.3	2.72

Table B.4: Bias coils (B_{bias}^x) measured current and hall probe voltage v.s. computer bias analogue voltage.

Computer Analogue Voltage (V)	Measured Current (A)	Hall Probe Voltage (V)
1.00	9.9	0.736
2.00	19.9	1.46
3.00	29.8	2.20
4.00	39.9	2.92
5.00	49.8	3.72
6.00	60.0	4.48
7.00	70.1	5.24
8.00	76.2	5.68
9.00	76.2	5.68

Table B.5: Bias coils (B_{bias}^y) measured current and hall probe voltage v.s. computer bias analogue voltage.

Computer Analogue Voltage (V)	Measured Current (A)	Hall Probe Voltage (V)
1.00	14.0	0.648
2.00	27.9	1.28
3.00	41.8	1.92
4.00	55.8	2.56
5.00	69.8	3.20
6.00	83.8	3.48
7.00	97.8	4.48
8.00	104.4	4.80
9.00	104.4	4.80

Table B.6: Bias coils (B_{bias}^z) measured current and hall probe voltage v.s. computer bias analogue voltage.

Anti-Helmholtz Coils	Conversion Factor	Distance to Center	Coil Diameter
units	G/cm/A	mm	mm
MOT	0.628	74	107
Transfer (Major Axis) (Minor Axis)	11.11 2.43	46.5	143 76
Helmholtz Coils	Conversion Factor	Distance to Center	Coil Diameter
units	G/A	mm	mm
Bias (x)	1.27	194	119
Bias (y)	1.22	179	147
Bias (z)	0.281	272	108

Table B.7: Table showing the physical characterisation parameters for MOT, transfer and bias coils.

Appendix C

Car Batteries Current Supply

The calibration of current generated by car batteries circuit diagram shown in Fig. 2.6 are plotted in Fig. C.1. The current values can be calculated from the hall voltage drops from the batteries. Fig. C.1 shows the hall voltage drops from corresponding number of batteries used.

Included also are the measured hall probe voltage which are directly related to the current driven to the system. By using the fitting parameters in Fig. C.1, the current can be known.

Figure C.1: Calibration of the hall probe voltage vs the current for car batteries.

No. of Batteries in series	Voltage Across Batteries (V)	Hall Probe Voltage (V)
1	12.1	0.64
2	24.2	1.28
3	36.4	1.80
4	48.6	2.36
5	60.3	2.56
6	71.5	2.68

Table C.1: Measured hall probe voltage of 12 V car batteries connected in series.

Bibliography

- Allen, John (2017). "Application of patterned illumination using a DMD for optogenetic control of signaling". In: *Nature Methods* 14.11.
- André, Axel et al. (2006). "A coherent all-electrical interface between polar molecules and mesoscopic superconducting resonators". In: *Nature Physics* 2.9, p. 636.
- Antoja Lleonart, Jordi (2014). "Study of the resistive switching phenomenon in YBCO superconducting samples". In:
- Bean, CHARLES P. (1964). "Magnetization of High-Field Superconductors". In: *Rev. Mod. Phys.* 36 (1), pp. 31–39.
- Berman, Paul R (1997). *Atom interferometry*. Academic press.
- Braginski, Alex I and John Clarke (2004). *The SQUID handbook*. Wiley-VCH.
- Brandt, Ernst Helmut (1996a). "Superconductors of finite thickness in a perpendicular magnetic field: Strips and slabs". In: *Phys. Rev. B* 54 (6), pp. 4246–4264.
- (1996b). "Superconductors of finite thickness in a perpendicular magnetic field: Strips and slabs". In: *Physical review B* 54.6, p. 4246.
- Cano, D. et al. (2011). "Experimental system for research on ultracold atomic gases near superconducting microstructures". In: *The European Physical Journal D* 63.1, pp. 17–23.
- Chan, Kin Sung (2014). "Vortex based atom traps and atomic electrometry on a superconducting atom chip". PhD thesis.
- Chen, Minghan (2005). *Optical studies of high temperature superconductors and electronic dielectric materials*. University of Florida.
- Clark, DE, WB White, and AJ Machiels (1986). "CRC handbook of laser science and technology". In:
- Cooper, Leon N. (1956a). "Bound Electron Pairs in a Degenerate Fermi Gas". In: *Phys. Rev.* 104 (4), pp. 1189–1190.
- Cooper, Leon N (1956b). "Bound electron pairs in a degenerate Fermi gas". In: *Physical Review* 104.4, p. 1189.
- De Aquino, Fran (2012). *Superconducting State generated by Cooper Pairs bound by Intensified Gravitational Interaction*.
- De Haas, WJ and A Rademakers (1940). "The thermal conductivity of lead in the superconducting and normal state". In: *Physica* 7.10, pp. 992–1002.
- Dekker, NH et al. (2000). "Guiding neutral atoms on a chip". In: *Physical Review Letters* 84.6, p. 1124.
- Demtröder, Wolfgang (2006). "Experimentalphysik 2". In: *Elektrizität und Optik, Kapitel 10*.

- Dikovsky, V. et al. (2005). "Reduction of magnetic noise in atom chips by material optimization". In: *The European Physical Journal D - Atomic, Molecular, Optical and Plasma Physics* 35.1, pp. 87–95.
- Dudley, Dana and Cheraina Dunn (2006). "DLP technology-not just for projectors and TVs". In: *Photonik international*, pp. 98–101.
- Dumke, R and Christoph (2018). "Life time of ultra cold atoms". In: *Private Communication*.
- Edwards, Mark (2013). "Ultracold gases: Atom SQUID". In: *Nature Physics* 9.2, p. 68.
- Edwards, W. Farrell (1981). "Classical Derivation of the London Equations". In: *Phys. Rev. Lett.* 47 (26), pp. 1863–1866.
- Etzold, Fabian (2010). "Laser Beam Shaping with a Digital Micromirror Device". PhD thesis.
- Farach, C. P. Poole H. A. and R. J. Creswick (1995). "Phenomenon of superconductivity In Superconductivity, chapter 2, pages 23 59". In: *Academic Press*.
- Fermani, R et al. (2010). "Heating rate and spin flip lifetime due to near-field noise in layered superconducting atom chips". In: *Journal of Physics B: Atomic, Molecular and Optical Physics* 43.9, p. 095002.
- Fernholz, T. et al. (2008). "Fully permanent magnet atom chip for Bose-Einstein condensation". In: *Phys. Rev. A* 77 (3), p. 033409.
- Foot, Christopher J et al. (2005). *Atomic physics*. Vol. 7. Oxford University Press.
- Fortágh, J. et al. (2002). "Surface effects in magnetic microtraps". In: *Phys. Rev. A* 66 (4), p. 041604.
- Ginzburg, Vitaly L (1955). "On the theory of superconductivity". In: *Il Nuovo Cimento (1955-1965)* 2.6, pp. 1234–1250.
- Ginzburg, VL and LD Landau (1950). "On superconductivity theory". In: *Zhurnal Eksperimental'noi i Teoreticheskoi Fiziki* 20, p. 1064.
- Goa, PE et al. (2003). "Magneto-optical imaging setup for single vortex observation". In: *Review of scientific instruments* 74.1, pp. 141–146.
- Günther, A. et al. (2007). "Atom Interferometer Based on Phase Coherent Splitting of Bose-Einstein Condensates with an Integrated Magnetic Grating". In: *Phys. Rev. Lett.* 98 (14), p. 140403.
- Gustavson, TL, A Landragin, and MA Kasevich (2000). "Rotation sensing with a dual atom-interferometer Sagnac gyroscope". In: *Classical and Quantum Gravity* 17.12, p. 2385.
- Hänsel, W. et al. (Oct. 2001). "Bose-Einstein condensation on a microelectronic chip". In: *Nature* 413, 498 EP –.
- Henkel, C., S. Pötting, and M. Wilkens (1999). "Loss and heating of particles in small and noisy traps". In: *Applied Physics B* 69.5, pp. 379–387.
- Henkel, C. and M. Wilkens (1999). "Heating of trapped atoms near thermal surfaces". In: *EPL (Europhysics Letters)* 47.4, p. 414.
- Henkel, C. et al. (2003). "Fundamental limits for coherent manipulation on atom chips". In: *Applied Physics B* 76.2, pp. 173–182.

- Hohenester, Ulrich et al. (2007). "Spin-flip lifetimes in superconducting atom chips: Bardeen-Cooper-Schrieffer versus Eliashberg theory". In: *Phys. Rev. A* 76 (3), p. 033618.
- Horowitz, M et al. (1952). "The specific heat of lead in the temperature range 1 K to 75 K". In: *Physical Review* 88.5, p. 1182.
- Jackson, John David (1999). "Classical electrodynamics". In: AAPT. Chap. Section 5.18A.
- Jessen, F. et al. (2014). "Trapping of ultracold atoms in a $^3\text{He}/^4\text{He}$ dilution refrigerator". In: *Applied Physics B* 116.3, pp. 665–671.
- Jones, M. P. A. et al. (2003). "Spin Coupling between Cold Atoms and the Thermal Fluctuations of a Metal Surface". In: *Phys. Rev. Lett.* 91 (8), p. 080401.
- Keil, Mark et al. (2016). "Fifteen years of cold matter on the atom chip: promise, realizations, and prospects". In: *Journal of Modern Optics* 63.18, pp. 1840–1885.
- Kezuka, H et al. (1991). "Refractive index of high-Tc YBCO superconductors". In: *Physica C: Superconductivity* 185, pp. 999–1000.
- Kunert, P. J. et al. (2014). "A planar ion trap chip with integrated structures for an adjustable magnetic field gradient". In: *Applied Physics B* 114.1, pp. 27–36.
- Lacroute, C. et al. (2010). "Preliminary results of the trapped atom clock on a chip". In: *IEEE Transactions on Ultrasonics, Ferroelectrics, and Frequency Control* 57.1, pp. 106–110.
- Leanhardt, A. E. et al. (2003). "Bose-Einstein Condensates near a Microfabricated Surface". In: *Phys. Rev. Lett.* 90 (10), p. 100404.
- Lin, X. E. (1999). "Laser pulse heating". In: *Proceedings of the 1999 Particle Accelerator Conference (Cat. No.99CH36366)*. Vol. 2, 1429–1431 vol.2.
- Lin, Yu-ju et al. (2004). "Impact of the Casimir-Polder Potential and Johnson Noise on Bose-Einstein Condensate Stability Near Surfaces". In: *Phys. Rev. Lett.* 92 (5), p. 050404.
- London, F. and H. London (1935). "The Electromagnetic Equations of the Supraconductor". In: *Proceedings of the Royal Society of London. Series A, Mathematical and Physical Sciences* 149.866, pp. 71–88.
- MEHTA, N. (2008). *Textbook of Engineering Physics*. pt. 1. PHI Learning.
- Meissner, W. and R. Ochsenfeld (1933). "Ein neuer Effekt bei Eintritt der Supraleitfähigkeit". In: *Naturwissenschaften* 21.44, pp. 787–788.
- Mukai, T. et al. (2007). "Persistent Supercurrent Atom Chip". In: *Phys. Rev. Lett.* 98 (26), p. 260407.
- Müller, T et al. (2008a). "Towards a guided atom interferometer based on a superconducting atom chip". In: *New Journal of Physics* 10.7, p. 073006.
- Müller, T. et al. (2010). "Programmable trap geometries with superconducting atom chips". In: *Phys. Rev. A* 81 (5), p. 053624.
- Müller, T et al. (2010a). "Programmable trap geometries with superconducting atom chips". In: *Physical Review A* 81.5, p. 053624.

- Müller, T et al. (2010b). "Trapping of ultra-cold atoms with the magnetic field of vortices in a thin-film superconducting micro-structure". In: *New Journal of Physics* 12.4, p. 043016.
- Müller, T et al. (2010c). "Trapping of ultra-cold atoms with the magnetic field of vortices in a thin-film superconducting micro-structure". In: *New Journal of Physics* 12.4, p. 043016.
- Müller, Tobias et al. (2008b). "Towards a guided atom interferometer based on a superconducting atom chip". In: *New Journal of Physics* 10.7, p. 073006.
- Nirrengarten, T. et al. (2006). "Realization of a Superconducting Atom Chip". In: *Phys. Rev. Lett.* 97 (20), p. 200405.
- Onnes, H. Kamerlingh (1991). "Further experiments with Liquid Helium. G. On the Electrical Resistance of Pure Metals, etc. VI. On the Sudden Change in the Rate at which the Resistance of Mercury Disappears." In: *Through Measurement to Knowledge: The Selected Papers of Heike Kamerlingh Onnes 1853–1926*. Ed. by Kostas Gavroglu and Yorgos Goudaroulis. Dordrecht: Springer Netherlands, pp. 267–272.
- Ott, H. et al. (2001). "Bose-Einstein Condensation in a Surface Microtrap". In: *Phys. Rev. Lett.* 87 (23), p. 230401.
- Pu, Song (1999). *Heat Transport in the High-temperature Superconductor Yttrium Barium Copper Oxide*. McGill University.
- Pyragius, Tadas (2012). "Developing and building an absorption imaging system for Ultracold Atoms". In: *arXiv preprint arXiv:1209.3408*.
- Romero-Isart, Oriol et al. (2013). "Superconducting vortex lattices for ultracold atoms". In: *Physical review letters* 111.14, p. 145304.
- Roux, C. et al. (2008a). "Bose-Einstein condensation on a superconducting atom chip". In: *EPL (Europhysics Letters)* 81.5, p. 56004.
- Roux, Cédric et al. (2008b). "Bose-Einstein condensation on a superconducting atom chip". In: *EPL (Europhysics Letters)* 81.5, p. 56004.
- Savalli, V. et al. (2002). "Specular Reflection of Matter Waves from a Rough Mirror". In: *Phys. Rev. Lett.* 88 (25), p. 250404.
- Scheel, S. et al. (2006). "Quantum Gates and Decoherence". In: *Quantum Coherence: From Quarks to Solids*. Ed. by Walter Pötz, Ulrich Hohenester, and Jaroslav Fabian. Berlin, Heidelberg: Springer Berlin Heidelberg, pp. 47–81.
- Scheel, Stefan and E. A. Hinds (2011). *Atoms at Micrometer Distances from a Macroscopic Body*. Wiley-VCH Verlag GmbH Co. KGaA, pp. 119–146.
- Schumm, T. et al. (Sept. 2005a). "Matter-wave interferometry in a double well on an atom chip". In: *Nature Physics* 1, 57 EP –.
- Schumm, Thorsten et al. (2005b). "Matter-wave interferometry in a double well on an atom chip". In: *Nature physics* 1.1, p. 57.
- Shaviv, R et al. (1990). "The heat capacity and derived thermophysical properties of the high TC superconductor YBa₂Cu₃O_{7-δ} from 5.3 to 350 K". In: *The Journal of Chemical Physics* 92.11, pp. 6794–6799.

- Sidorov, A. and P. Hannaford (2011). "From Magnetic Mirrors to Atom Chips". In: *Atom Chips*. Wiley-VCH Verlag GmbH Co. KGaA, pp. 1–31.
- Siercke, M. et al. (2012a). "Reconfigurable self-sufficient traps for ultracold atoms based on a superconducting square". In: *Phys. Rev. A* 85 (4), p. 041403.
- Siercke, M et al. (2012b). "Reconfigurable self-sufficient traps for ultracold atoms based on a superconducting square". In: *Physical Review A* 85.4, p. 041403.
- Sinclair, C. D. J. et al. (2005). "Bose-Einstein condensation on a permanent-magnet atom chip". In: *Phys. Rev. A* 72 (3), p. 031603.
- Skagerstam, Bo-Sture K. and Per Kristian Rekdal (2007). "Photon emission near superconducting bodies". In: *Phys. Rev. A* 76 (5), p. 052901.
- Skagerstam, Bo-Sture K. et al. (2006). "Spin Decoherence in Superconducting Atom Chips". In: *Phys. Rev. Lett.* 97 (7), p. 070401.
- Smith, David A et al. (2008). "Experimental single-impulse magnetic focusing of launched cold atoms". In: *Journal of Physics B: Atomic, Molecular and Optical Physics* 41.12, p. 125302.
- Smith, David A et al. (2011). "Absorption imaging of ultracold atoms on atom chips". In: *Optics express* 19.9, pp. 8471–8485.
- Sørensen, Anders S et al. (2004). "Capacitive coupling of atomic systems to mesoscopic conductors". In: *Physical review letters* 92.6, p. 063601.
- Stick, D. et al. (Dec. 2005). "Ion trap in a semiconductor chip". In: *Nature Physics* 2, 36 EP –.
- Tair, Fadila et al. (2017). "Melting temperature of $\text{YBa}_2\text{Cu}_3\text{O}_{7-x}$ and $\text{GdBa}_2\text{Cu}_3\text{O}_{7-x}$ at subatmospheric partial pressure". In: *Journal of Alloys and Compounds* 692, pp. 787–792.
- Tešanović, Zlatko et al. (1992). "Critical fluctuations in the thermodynamics of quasi-two-dimensional type-II superconductors". In: *Physical Review Letters* 69.24, p. 3563.
- Testardi, L. R. (1971a). "Destruction of Superconductivity by Laser Light". In: *Phys. Rev. B* 4 (7), pp. 2189–2196.
- Testardi, LR (1971b). "Destruction of superconductivity by laser light". In: *Physical Review B* 4.7, p. 2189.
- Treutlein, Philipp et al. (2004). "Coherence in Microchip Traps". In: *Phys. Rev. Lett.* 92 (20), p. 203005.
- Veshchunov, I. S. et al. (Sept. 2016). "Optical manipulation of single flux quanta". In: *Nature Communications* 7, 12801 EP –.
- Wang, Ying-Ju et al. (2005). "Atom Michelson interferometer on a chip using a Bose-Einstein condensate". In: *Physical review letters* 94.9, p. 090405.
- Whitlock, S. (2007). "Bose-Einstein condensates on a magnetic film atom chip". In: *PhD thesis, Faculty of Engineering and Industrial Sciences, Centre for Atom Optics and Ultrafast Spectroscopy*.
- Wu, Saijun, Edward Su, and Mara Prentiss (2007). "Demonstration of an area-enclosing guided-atom interferometer for rotation sensing". In: *Physical review letters* 99.17, p. 173201.

- Zhang, B. et al. (2010a). "Design of magnetic traps for neutral atoms with vortices in type-II superconducting microstructures". In: *Phys. Rev. A* 81 (6), p. 063408.
- Zhang, B et al. (2010b). "Design of magnetic traps for neutral atoms with vortices in type-II superconducting microstructures". In: *Physical Review A* 81.6, p. 063408.
- Zhang, B. et al. (2012a). "Magnetic confinement of neutral atoms based on patterned vortex distributions in superconducting disks and rings". In: *Phys. Rev. A* 85 (1), p. 013404.
- Zhang, B et al. (2012b). "Magnetic confinement of neutral atoms based on patterned vortex distributions in superconducting disks and rings". In: *Physical Review A* 85.1, p. 013404.