Toward Atomtronic Devices

RAINER DUMKE[1-2] AND LUIGI AMICO[2-4]
[1]DIVISION OF PHYSICS AND APPLIED PHYSICS, NANYANG TECHNOLOGICAL UNIVERSITY, SINGAPORE
[2]CENTER FOR QUANTUM TECHNOLOGIES, NATIONAL UNIVERSITY OF SINGAPORE, SINGAPORE
[3]DIPARTIMENTO DI FISICA E ASTRONOMIA, UNIVERSITÀ CATANIA, ITALY
[4]CNR-IMM UOS UNIVERSITÀ (MATIS), CONSIGLIO NAZIONALE DELLE RICERCHE & INFN, ITALY

ABSTRACT

This brief review covers the recent developments in a new emerging subfield of ultracold atoms: atomtronics, in which cold atoms trapped in optical fields or lattices are manipulated for the development of electronic and optical devices.

KEYWORDS

Atomtronics, cold atoms, optical traps, quantum and mesoscopic devices.

INTRODUCTION

In recent years, research into cold and ultracold atoms has witnessed significant developments with remarkable advancements in optical trapping and cooling. It is now possible to control, manipulate and tune the knobs in the experiments precisely over a wide range of parameters, with better equipment and more sophisticated probes. Cold atom systems have also served as quantum analogue computers (see recent articles in [1,2]), capable of mimicking the properties and dynamics of many-body quantum systems, both in weakly interacting regimes and strongly correlated regimes. Moreover, the state of the art in quantum degenerate Bose and Fermi gases in periodic lattices has reached the stage where we can now study and understand many exotic Hamiltonians at the microscopic level.

Electronic devices rely on the flow of electrons and holes for transport and functionality. With advancements in the techniques for ultracold atoms, can we replace the electrons by these cold atoms in electronic circuitry and devices? What advantages do we gain and what challenges do we face?

A promising emerging field in physics that may realize these atomic circuit architectures is the emerging field of atomtronics. Atomtronics exploits ultra-cold atoms and manipulates them in versatile micro-optical circuits generated by laser fields of different shapes and intensities or by micro-magnetic circuits known as atom chips. So what does atomtronics promise?

- The technology to create a defect free optical lattice has been advancing rapidly and, experimentally, optical lattices offer an extremely clean medium for the flow of ultracold atoms. These atoms move seamlessly through the optical lattices with little dissipation, something electrons cannot do.

- Atomtronic devices are potentially richer than their electronic counterparts. Atoms possess more degrees of freedom than electrons. Aside from charge, as well as spin, atoms can exist as bosons or fermions, providing completely different statistical and quantum behavior.

- Moreover, there is a variety of interaction between the atoms. Atoms can interact within short or long ranges, their interaction strength could be tuned from weak to strong (for instance, through Feshbach resonances), and depending on their intrinsic properties, their behavior can range from repulsive to attractive.

- Current experimental techniques allow the detection of atoms with fast, state-resolved and near-unit quantum efficiency. Thus, in principle it is possible to follow the dynamics of an atomtronic system in real time.

- Atoms in optical lattices can also provide an interesting platform to implement mesoscopic devices such as single electron transistors. This feature can lead to a plethora of insights into mesoscopic physics. Recent experiments into transport properties of ultra-cold atoms in optical lattices can be delved at length in the context of the atomtronics framework. In particular, one can model the short-time transport properties of an optical lattice with an open quantum system.

- Neutral atoms in optical lattices can be well isolated from the environment, reducing decoherence. Combined with a powerful means of state readout and preparation and methods for entangling atoms, such systems have all the necessary ingredients to be the building blocks of quantum signal processors.

- In the context of solid-state I-V characteristics, a variety of physical phenomena in many-body physics could be studied with highly accurate and controllable quantum optics technology. Moreover, by exploiting the limits of current lithographic designs and precision, almost all aspects of mesoscopic physics and devices can also be explored. Not only is classical electronics targeted, but also atom-based spintronics and quantum electronic structures like Josephson-junction-based circuits (SQUID devices, etc.), quantum point contacts and impurity problems.

- Core devices for applications in quantum metrology (e.g., nano-scale amplifiers or precision sensors), can be designed and exploited. Atomtronics could also provide a new solution for the physical realization of quantum gates for quantum information protocols and hybrid quantum systems.

One of the first papers to mention the word "Atomtronics" in its title is probably a remarkable piece of work by Seaman, Kramer, Anderson and Holland [3] where they show that cold atoms trapped in a one dimensional optical lattice could mimic the band structure in a solid state system. Cold atoms confined to such a one-dimensional trap can be described effectively with a Bose-Hubbard Hamiltonian. Depending on the lattice hopping rate and the chemical potential, the atoms exhibit two distinct phases: a Mott insulating phase and a superfluid regime. Seaman *et al.* demonstrate that for a fixed hopping strength, the range of chemical potential for the Mott insulating phase could be regarded as a band gap and the interval between two Mott phases can be seen as a bandwidth (see Figure 1).

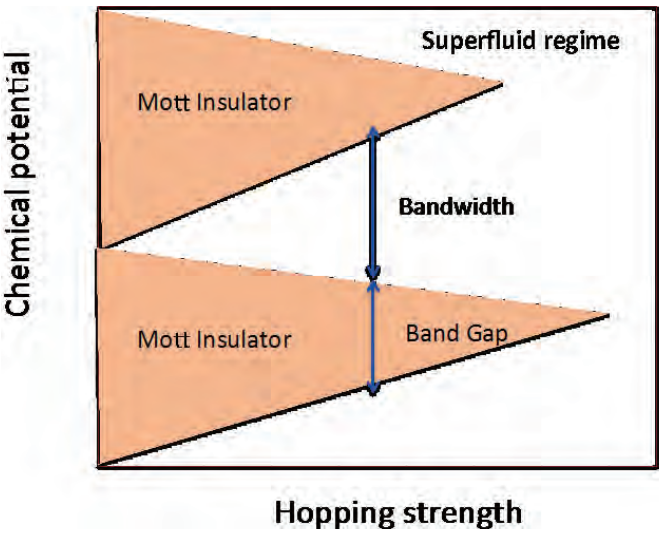

Fig. 1: Phase diagram of the Bose-Hubbard model showing the Mott insulating phase and the superfluid phase and the interpretation of band gap and band width. Figure extracted from Ref. [3].

Indeed, it has since been shown that it is possible to implement atomtronic circuits with diodes and transistors [4]. An atomtronic transistor is essentially a device with a triple-well potential. The three wells mimic the source, gate and drain in a normal transistor device. In such a device, the source-gate chemical potential difference controls the flow of atoms through the potential.

For several years, we have been working toward loading cold atoms into ring optical lattices with the hope that we can demonstrate atomtronic devices at the mesocopic scale. We have shown that by cranking up one of the barriers in the optical lattice, we can mimic a weak link and the optical lattice can serve as a qubit through coherent superposition of the persistent currents [6-8].

The set-up is also essentially an atomic analogue of the superconducting interference device (SQUID) or an AQUID, in short. By varying the number of weak links in the lattice, we could also display other quantum effects.

Ring Optical Lattices

To construct a ring optical lattice, we made use of the rotational symmetry of Laguerre-Gauss (LG) modes to produce closed optical lattices. The LG beams are obtained experimentally by making use of computer generated holograms, a technique that has already been widely deployed in the field of ultra-cold atoms [5]. The LG mode with frequency ω, wave vector k and amplitude E_0 propagating along the z axis can be written in cylindrical coordinates (r,ϕ,z) as

$$E(r,\phi,z) = E_0 f_{pl}(r) e^{il\phi} e^{i(\omega t - kz)}$$

where $f_{pl}(r)$ denotes the function

$$f_{pl}(r) = (-1)^p \sqrt{\frac{2p!}{\pi(p+|l|)}} \varepsilon^l L_p^{|l|}(\varepsilon^2) e^{\varepsilon^2}$$

where r_0 is a waist of a beam and $L_p^{|l|}$ are associate Laguerre polynomials. The numbers p and l label the radial and azimuthal quantum coordinates respectively.

Experimentally, the light is split into the two sides of our system, with 10% of the light in the 'monitoring' arm, and 90% into the 'trapping' arm used to create a red-detuned dipole trapping potential for a gas of Rb 87 atoms. A Ti:Saph laser (Coherent MBR-110) produces a 1 W, 828 nm beam, which is spatially filtered and collimated, before reflection on the SLM. To produce the trapping potential, the SLM's kinoform is imaged through a 4f lens system, reducing the beam size to a diameter of 3 mm, and focused through a 50× microscope objective with a 4 mm focal distance and a numerical aperture of NA of 0.42 (Mitutoyo 50× NIR M-Plan APO). The monitoring arm of the system creates an image of the potential through a 10× infinity- corrected microscope objective focused on a CCD camera (PointGrey FL3-GE-13-S2M-C). The CCD camera views, therefore, an enlarged image of the optical potential.

The SLM is comprised of a liquid-crystal-on-silicon display, with 8-bit phase values from 0 to 2π, covering a 15.36 mm by 8.64 mm region with a filling factor of 87%. The individual pixels create a phase-shift pattern (kinoform) on the incoming light, which can be used to create arbitrary 2D optical potentials on the image-plane of a Fourier transforming lens. To construct the kinoform applied to the SLM we used an improved version of the mixed-region-amplitude-freedom (MRAF) algorithm [41,42] with angular spectrum propagator. A region outside of the desired pattern is used to collect unwanted light contributions that result from the iterative MRAF algorithm. The MRAF algorithm iteratively finds a solution to minimize the error, within the region of interest, between the computationally produced image

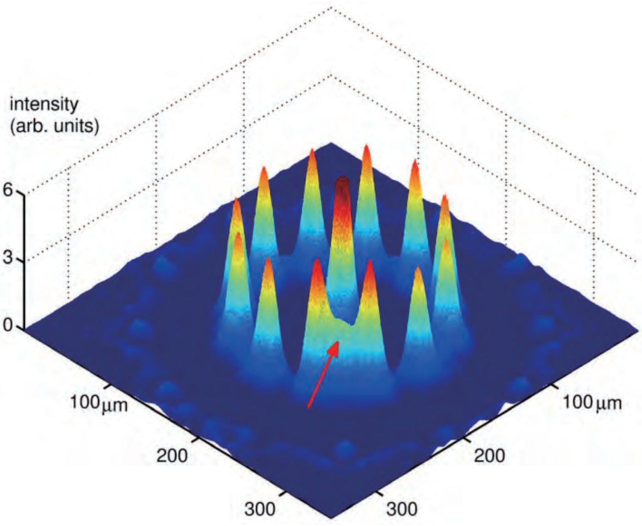

Fig. 2: Optical lattice with a weak link created through the SLM's kinoform.

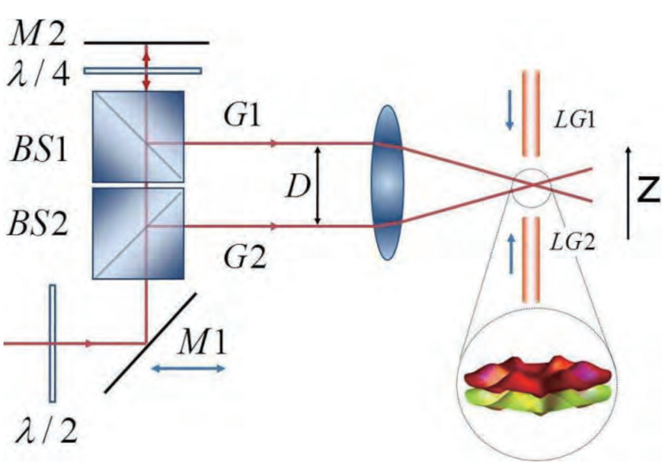

Fig. 3: The experimental set up for the generation of a ring-like optical lattice.

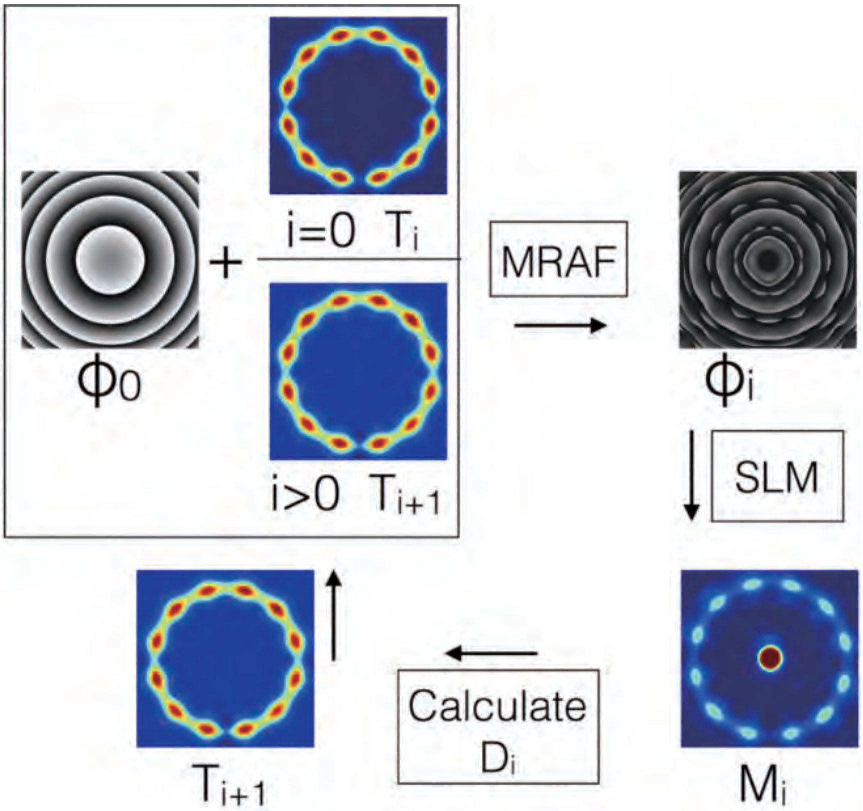

Fig. 4: Algorithm for generating the optical lattice.

(the Fourier transform of the kinoform) and the desired result. However, when this kinoform is applied to the SLM there arise additional errors due to imperfections in the SLM and aberrations in the optics.

Single- and Two-Ring Qubits

To break Galilean invariance, we need to load the cold atoms into a single ring-shaped potential with identical wells, but with a dimple located at one of the sites (see Fig. 1), and pierced by a 'magnetic flux' Φ, or with two homogeneous coupled rings . In Ref. [6-7], we have shown that both configurations provide a feasible two-level system.

We have shown that the dimple or weak link painted on the ring acts as a source of coherent back-scattering for the propagating gas, interfering with the forward scattered current. This system then defines an atomic counterpart of the rf-SQUID: an atomtronics quantum interference device. We have examined the dependence of the qubit energy gap on the bosonic density, the interaction strength, and the barrier depth, and we show how the superposition between current states appears in the momentum distribution (time-of-flight) images. A mesoscopic ring lattice with intermediate-to-strong interactions and weak barrier depth is found to be a favorable candidate for setting up, manipulating and probing a qubit in the next generation of atomic experiments [5].

Limitations of Atomtronics

Scientists are hoping to use the condensate in the way that superconductors have been used to make improved devices and sensors. An idea for a useful device was inspired by superconducting quantum interference devices, commonly known as SQUIDs. Scientists also believe that Bose-Einstein condensate could provide an extremely sensitive rotation sensor.

It is pointed out, however, that atomtronics probably would not replace electronics as atoms are sluggish compared to electrons. This means it might be difficult to replace fast electronic devices with sluggish atomtronic devices.

Finally, despite all the challenges, atomtronics promises to provide a platform for the rich exploration of physics and a possible opportunity for the application of our knowledge of cold atoms to real devices. Aside from realizing quantum computing devices and analogous electronic and spintronic devices, atomtronic devices have also been envisaged for a plethora of quantum metrology schemes and communication protocols.

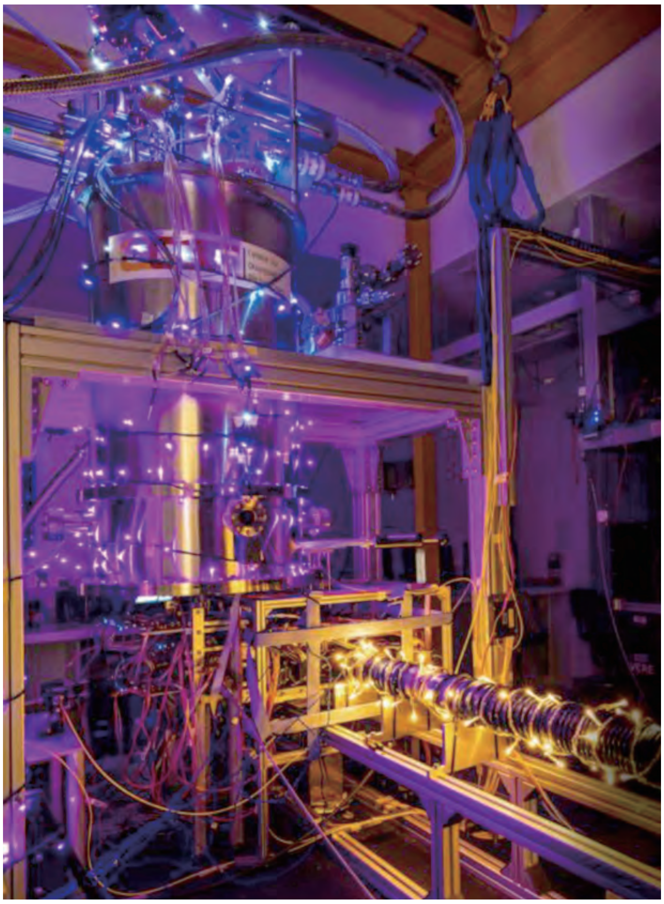

Fig. 5: The experimental apparatus as a Christmas Tree, December 2016.

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Rainer Dumke is the deputy head of the Division of Physics and Applied Physics at Nanyang Technological University and a principal investigator at the Center for Quantum Technologies at the National University of Singapore. He was awarded a prestigious fellowship from the Alexander von Humboldt foundation and he spent some time at NIST (Gaithersburg, USA) for his research on ultra cold molecules and quantum degenerate gases, before moving to a research position at the Max Planck Research Group in Erlangen, Germany.

Luigi Amico works at the Department of Physics and Astronomy, the University of Catania and is a member of CNR-MATIS Excellence Centre for Condensed Matter and Material Science, Italy, Dipartimento di Fisica e Astronomia, Universita´ Catania, Italy, CNR-IMM UOS Universita` (MATIS), Consiglio Nazionale delle Ricerche & INFN, Italy, LANEF 'Chaire d'excellence', Universite' Grenoble-Alpes & CNRS, France. Prof. Amico has been visiting research fellow in numerous international institutions including Augsburg University (Germany), Universidad Autonoma and Universidad Complutense (Madrid, Spain), Perimeter Institute for Theoretical Physics (Canada) and the Rutherford Appleton Laboratory (UK). He is also a visiting professor at the Centre for Quantum Technologies (Singapore).