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Beam Splitter for Guided Atoms

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We have designed and experimentally studied a simple beam splitter for guided atoms realized with a current carrying Y-shaped wire nanofabricated on a surface (*atom chip*). Such a Y-configuration beam splitter has many advantages compared to conventional designs based on tunneling, especially that it will enable robust beam splitting. This and other similar designs can be integrated into more sophisticated surface-mounted atom optical devices at the mesoscopic scale.

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Beam splitters are key elements in optics and its applications. In atom optics [1] beam splitters were, up to now, demonstrated only for atoms moving in free space, interacting either with periodic potentials (spatial and temporal), material gratings [2], or semitransparent mirrors [3]. On the other hand, guiding of atoms has attracted much attention in recent years and different guides have been realized using magnetic potentials [4–9], hollow fibers [10], and light potentials [11,12].

In this Letter we describe experiments which join the above, namely demonstrating a nanofabricated beam splitter for guided atoms using microscopic magnetic guides on an *atom chip* (see Fig. 1).

By bringing atoms close to electric and magnetic structures, one can achieve high gradients to create microscopic potentials with a size comparable to the de-Broglie wavelength of the atoms, in analogy to mesoscopic quantum electronics [13,14]. One possibility is to use the interaction $V = -\vec{\mu} \cdot \vec{B}$ between a neutral atom (magnetic moment $\vec{\mu}$) and the magnetic field $\vec{B}$ generated by current carrying structures [6,15,16]. The simplest configuration is a magnetic guide built using a straight wire carrying a current I. By adding a homogeneous bias field B_{bias} one can produce a two-dimensional minimum of the potential [17] and guide atoms in the low field seeking state parallel to the wire (side guide). Mounting the wires on a surface allows elaborate designs with thin wires which can sustain sizable currents [16]. Such surface mounted atom optical elements were recently demonstrated for large structures (wire size ≈100 μm) [7,18,19], and nanofabricated structures [9], the latter achieving the scales required for mesoscopic physics and quantum information proposals with microtraps [20].

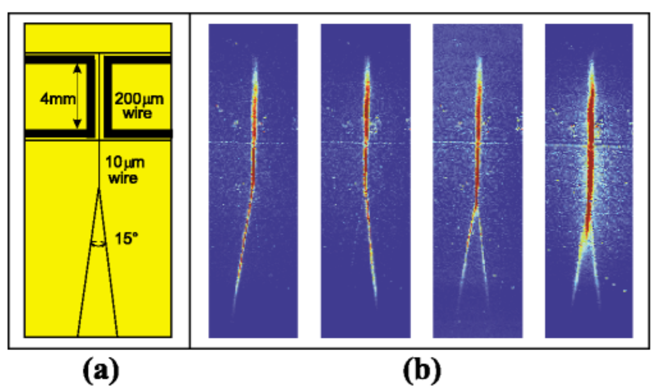

FIG. 1 (color). Beam splitter on a chip: (a) chip schematic and (b) fluorescence images of guided atoms. As explained in the text, the two large U-shaped 200 μm wires are used to load atoms onto the 10 μm Y-shaped wire. In the first two pictures in (b), we drive current through only one side of the Y, therefore guiding atoms either to the left or to the right; in the next two pictures, taken at two different guide gradients, the current is divided in equal parts and the guided atoms split into both sides.

By combining two guides, it is possible to design potentials where at some point two different paths are available for the atom. This can be realized using different configurations, among which the simplest and most advantageous is a Y-shaped wire [21,22] like the one shown in Fig. 1a. Such a beam splitter has one accessible input for the atoms, that is the central wire of the Y, and two accessible outputs corresponding to the right and left wires. Depending on how the current in the input wire is sent through the Y, atoms can be directed to the output arms with any desired ratio (Fig. 1b). In the experiment reported here, we study such a beam splitter created by a Y-shaped wire mounted on a nanofabricated atom chip.

Our experiments are carried out using laser cooled Li atoms. A detailed description of the apparatus and the atom trapping procedure is given in [9,23]. The atom chip consists of a 2.5 μm thick gold layer deposited onto a GaAs substrate. This gold layer is patterned using standard nanofabrication techniques. A schematic of the wires on the atom chip used for this experiment is shown in Fig. 1a. It includes, besides the beam splitter, a series of magnetic traps to transfer atoms into the small guide: large U-shaped wires, 200 μm wide, provide a quadrupole potential if combined with a homogeneous bias field [9,19,24], while the thin Y-shaped wire is 10 μm wide. In addition a 1 mm thick U-shaped wire underneath the chip assists with loading the atoms.

The atoms are loaded onto the atom chip using our standard procedure (see details in [9,19]): Typically 10^8 cold ^{7}Li atoms are accumulated in a "reflection magneto-optical trap (MOT)" [25,26] and transferred to the splitting potential in the following steps: Atoms are first transferred into the MOT generated by the quadrupole field of the U wire ($I = 17$ A, $B_{\text{bias}} = 6$ G) underneath the chip. Then, the laser light is switched off, leaving the atoms confined only by the magnetic quadrupole field of the U wire. Atoms are then further compressed and transferred into a magnetic trap generated by the two 200 μm wires on the chip ($I = 2$ A, $B_{\text{bias}} = 12$ G), compressed again and transferred into the 10 μm guide ($I = 0.8$ A, $B_{\text{bias}} = 12$ G). Each compression is achieved by decreasing the current generating the larger trap to zero and simultaneously switching on the current generating the smaller trap over a time of 10 ms. We transfer $>10^6$ atoms into the 10 μm guide [27]. For the beam splitter experiments we used guides characterized by a typical transverse trap frequency of $\omega \sim 2\pi \times 6$ kHz (distance between the two lowest transverse levels), a gradient of $\sim$1000 G/cm and a depth of $\sim$0.7 mK.

The properties of the beam splitter are investigated by letting the atoms propagate along the guide for some time due to their longitudinal thermal velocity. The resulting atom distribution is measured by fluorescence images taken by a CCD camera looking at the atom chip surface from above. For this, a short ($<$0.5 ms) molasses pulse is applied. The pictures shown in Fig. 1b are such images taken after 16 ms of guiding in the beam splitter. The first two pictures are obtained at $B_{\text{bias}} = 12$ G by sending 0.8 A only through one of the output wires; atoms can therefore turn either left or right. In the third and fourth pictures the atoms experience a splitting potential, the current being sent equally through both out-going arms of the Y-shaped wire. The images are taken at bias fields 12 G and 8 G, respectively. At 12 G the atoms are clearly more compressed.

By changing the ratio of the current between the two outputs, and simultaneously keeping the total current constant, it is possible to control the probability of emerging left or right. Typical data for a beam splitter experiment using an 8 G bias field are shown in Fig. 2. Here, the atom number in each arm, as determined by summing over the density distribution, is plotted versus the ratio between left arm current and input current. The side carrying more current is preferred due to the larger transverse size of the guiding potential. It can be noted that the 50/50 splitting ratio occurs for a current ratio different from one half. This is due to an additional 3 G field directed along the input guide to make a Ioffe-Pritchard configuration and prevent Majorana spin flips; such a field introduces a difference in the output guides which can be compensated with different currents. The solid lines shown in Fig. 2 are obtained with Monte Carlo simulations of an atomic sample at $T = 250$ μK propagating in the Y beam splitter.

Before discussing our beam splitter in detail, one should note some properties of the potential created by the Y-shaped wire and a homogeneous bias field as shown in Fig. 3: (1) For the in-coming arm of the Y and for the two out-going arms, far away from the splitting point, we have simple side guide potentials. (2) The potential for

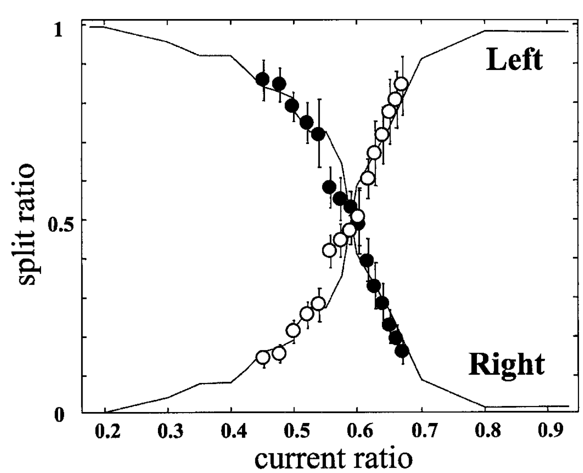

FIG. 2. Switching atoms between left and right by changing the current ratio in the two outputs and keeping the input current constant at 0.8 A. The atomic splitting ratio is reported versus the ratio between left arm current and input current. The points are measured values while the lines are obtained from Monte Carlo (MC) simulations. The kinks in the lines are due to MC statistics.

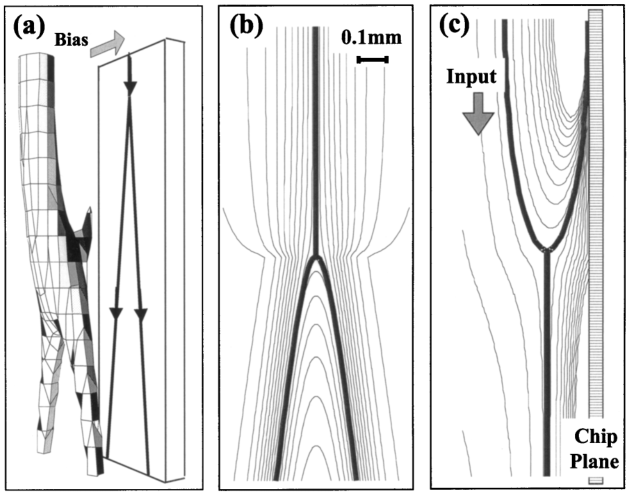

FIG. 3. Detailed properties of the Y splitting potential: (a) shows the 1.5 G equipotential surface above the *atom chip*; (b) shows the position of the potential minima (thick line) projected onto the chip surface; (c) shows the minima location above the surface. A second minimum closer to the chip surface occurs in the region between the wire splitting and the actual split point of the potential. The plots in (b) and (c) also show equipotential lines at $1, 2, \ldots, 6$ G. These plots are generated at wire current 0.8 A and $B_{\rm bias} = 6$ G.

the two out-going guides is tighter (twice the gradient) than for the in-coming guide and its minimum is at half distance from the chip surface. This is caused by the fact that the in-coming guide is formed by a current which is twice that of the out-going guides. It should also be noted that due to the change in direction of the output wires, the bias field has now a component along the guides which contributes to the Ioffe-Pritchard field. (3) The splitting point of the potentials is *not* at the geometrical splitting point of the wires. This can be seen in the pictures of Fig. 1b. The actual split point of the potential is located after the geometrical split. Precisely, it occurs when the distance between the output wires is given by $d_{\rm split} = \frac{\mu_o}{2\pi}\frac{I}{B_{\rm bias}}$, which is equal to the height above the chip of the input guide. (4) An additional potential minimum appears between the geometric splitting point of the Y wire and the splitting point of the potential, forming a fourth port, which induces a loss rate since atoms taking that route will hit the surface.

The different location of the potential split, and the additional inaccessible fourth port of the beam splitting potential, can be explained simply by taking two parallel wires with current in the same direction and adding a homogeneous bias field along the plane containing the wires and directed orthogonal to them (see also [28]). Depending on the distance d between the wires one observes three different cases: (i) If $d < d_{\rm split}$, two minima are created one above the other on the axis between the wires. In the limit of d going to zero the minimum closer to the wires plane falls onto it. (ii) If $d = d_{\rm split}$, the two minima fuse into one. (iii) If $d > d_{\rm split}$ two minima are created one above each wire. The barrier between them increases with the wire distance and we eventually obtain two independent guides. In the Y beam splitter one encounters all three cases moving along the beam splitter axis, as shown in detail in Figs. 3b and 3c.

The dynamic of an atom propagating through the Y beam splitter potential is best described by a scattering process in restricted space from in-coming modes into out-going modes. As with scattering in free space, we expect some back scattering into the in-coming mode, unless the propagation is adiabatic. For example, reflection can occur because the output guides have higher transverse gradients which results in a mismatch of modes. Another contribution comes from the vertical direction change of the input guide as it gets closer to the chip surface. From the atomic distribution observed in the experiment we could estimate a back reflection of less than 20% at the splitting point.

The Y configuration enables a 50/50 splitting over a wide range of experimental parameters due to its *inherent symmetry* relative to the incoming guide axis. By inherent we mean that the symmetry of the potential is maintained for different magnitude of current and bias field, and for different incoming transverse eigenmodes. The atom arriving at the splitting junction with definite transverse parity encounters a symmetric scattering potential, and will thus have equal right-left amplitudes regardless of the specific current and bias field in use. This was also numerically confirmed up to the first 35 modes. Therefore, such a beam splitter will allow inherently coherent splitting for multimode propagation, as long as the total incoming state is some incoherent sum of the eigenmodes (e.g., a thermal state). We note, that the specific evolution of such a thermal state through an interferometer, comprising of two back to back Y beam splitters, has been calculated and will be presented elsewhere. Finally, this symmetric splitting may be corrupted only by breaking the symmetry of the potential, for example by a rotation of the bias field direction or by altering the current ratio in the output arms.

This is an advantage over beam splitter designs for guided matter waves which rely on tunneling [29], where the potential at the closest point exhibits two guides separated by a potential barrier, which has to be very thin (<1 μm) or very shallow. The splitting ratio depends on the tunneling probability, which is vastly different for different propagating transverse modes and longitudinal velocities. A further disadvantage is that the barrier width and height are sensitive to changes in the current and bias field, and therefore even for a single mode the splitting will be extremely sensitive to external parameters.

The backscattering and the inaccessible fourth port of our realization of a Y beam splitter may be, at least partially, overcome using different beam splitter designs as shown in Fig. 4. One configuration (Fig. 4a) has two wires running parallel until a given point and then going apart. If the input guide fulfills case (ii) of the above discussion, the

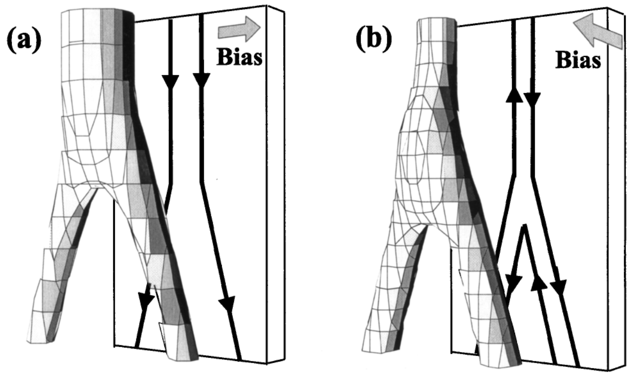

FIG. 4. Y beam splitter designs: The splitting potential in (a) is realized with two wires running parallel until a given point and then going apart; (b) is a more advanced Y beam splitter where the output guides have the same characteristics as the input guide, in order to minimize the backscattered amplitude.

splitting point of the potential is at the parting of the wires and the height of the potential minimum above the chip surface is maintained throughout the device (in the limit of small opening angle), and no fourth port appears in the splitting region. In Fig. 4b we present a more advanced design where the guide is realized using two parallel wires with currents in opposite directions and a bias field perpendicular to the chip surface. The splitting potential is designed in order to have (nearly) identical input and output guides, minimizing reflections due to different guide gradients.

In conclusion, we have realized a beam splitter for guided atoms, with a design that ensures symmetry under a wide range of experimental parameters, and which can be further developed to bypass its main drawbacks. This device could find applications in atom interferometry and in the study of decoherence processes close to a surface. Furthermore, this basic element could be integrated into more complex quantum networks which would form the base for advanced applications such as quantum information processing.

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Note added.—After the preparation of this manuscript, we became aware of two other beam splitter experiments for guided atoms [30].

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counterpropagating beams on the third axis, parallel to the chip surface. The MOT quadrupole is produced by coils with their axis parallel to one of the 45° laser beams (see also [19]). After loading the MOT, the atoms are cooled to below 200 μK by shortly changing intensity and detuning of the laser beams.

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