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Fast Josephson vortex ratchet made of intrinsic Josephson junctions in $Bi_2Sr_2CaCu_2O_8$

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We demonstrate the operation of a deterministic fluxon ratchet made of a stack of 30 intrinsic $Bi_2Sr_2CaCu_2O_8$ Josephson junctions. The ratchet has the shape of a gear with 20 asymmetric teeth (periods). It produces a rectified voltage of about 100 μV at a 12 GHz drive frequency. The effect of coupling between intrinsic junctions, i.e., the mode of fluxon motion for ratchet operation, has been studied within the framework of the two-dimensional coupled sine-Gordon equations. Further, we used low-temperature scanning laser microscopy to demonstrate that voltage rectification indeed is due to directed fluxon motion, in agreement with numerical simulations.

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Ratchets, initially invented by engineers to provide a unidirectional motion in mechanical systems such as watches, were used by physicists during the 20th century to test fundamental scenarios in thermodynamics and statistical physics (Maxwell Demon, Feynman Ratchet, etc). In the last decade, being still important for applications such as nanoparticle separation, ratchets were found to be important for muscles operation and for anomalous transport.[1–3] Simultaneously, ratchets realized using solid-state systems and, in particular, superconductors attract more and more attention because they have a number of advantages. In the simplest case, a ratchet consists of a particle moving in an asymmetric periodic potential under the action of stochastic and/or deterministic forces with zero time average. The ultimate goal of any ratchet is to *rectify* this force and produce a unidirectional (in average) motion of a particle. In the superconducting systems the role of a particle can be played by an Abrikosov vortex,[4–8] a Josephson vortex,[9–14] or it can be a fictitious particle representing the Josephson phase.[15–19] In such structures the average motion of the "particle" can be detected by measuring the average dc voltage V across the structure. While Abrikosov vortex ratchets typically rectify input frequencies from dc up to few MHz, the Josephson ratchets show rectification from dc up to tens of GHz and can operate in overdamped,[18,19] underdamped,[11–14] and even quantum[17] regimes.

The frequency band usable for rectification is one of the most important figure of merit, showing how much spectral energy can be potentially captured and rectified. In a Josephson vortex ratchet the maximum rectifiable frequency cannot exceed $f_{\max}=v_{\max}/L_1$, where $v_{\max}=c_s=2\pi f_{pl}\lambda_J$ is the maximum fluxon velocity, c_s is the Swihart velocity ($\sim$2% of the vacuum speed of light c), L_1 is the period of the ratchet potential, f_{pl} is the Josephson plasma frequency and λ_J is the Josephson length ($\sim$20 μm). L_1 cannot be decreased below $\sim 4\lambda_J$ to allow for the formation of a fluxon. Thus, $f_{\max} \lesssim f_{pl} \lesssim 100$ GHz. The typical values quoted above refer to standard Nb tunnel junctions. Another important characteristic for Josephson ratchets is the maximum rectified dc voltage $V_{\max}$. Assuming periodic dynamics, $V_{\max}=\Phi_0 f_{\max}/n = \Phi_0 v_{\max}/L$, where $\Phi_0=2.07\times 10^{-15}$ Wb is the magnetic-flux quantum and $n=L/L_1$ is the number of periods of the potential along an annular junction with circumference L. For existing fluxon ratchets, $V_{\max}\lesssim 30$ μV for $n=1$ was measured.[14]

To improve both $f_{\max}$ and $V_{\max}$ one should increase $v_{\max}$. Moreover, to improve $V_{\max}$ one can combine several ratchets in series. An intriguing option to realize both of these ideas is to use a stack of many intrinsic Josephson junctions (IJJs) (Refs. 20 and 21) formed between adjacent CuO_2 double layers in the high-temperature superconductor $Bi_2Sr_2CaCu_2O_8$ (BSCCO). For such IJJs, asymmetric (with respect to bias current) fluxon flow has been demonstrated.[22] The Josephson plasma frequency can be quite high, reaching values above 150 GHz.[23] However, each IJJ in a stack does not rectify independently. Having an individual thickness of 1.5 nm, each IJJ is strongly coupled with the neighbors by means of supercurrent flowing along the common CuO_2 planes. In an N junction stack containing m fluxons the maximum velocity $v_{\max}$ depends on N, m, and the fluxon distribution within the stack. For the simplest fluxon configurations the maximum velocities are given by $c_q = c_s/\sqrt{1-2s\cos[\pi q/(N+1)]}$ with $s\approx 0.5$ and $q=1,\ldots,N$.[24,25] While, for large N, the lowest velocity c_N is about $c_s/\sqrt{2}\sim 3\times 10^5$ m/s, the fastest velocity c_1 can approach $c/\sqrt{\epsilon}$, where ϵ is the dielectric constant of BSCCO. Although there are many other less regular (or more disordered) fluxon configurations, the range between c_N and c_1 gives a good idea about the possible velocity range. One might thus envision that if the fluxons move in phase (rectangular lattice) with $v_{\max}=c_1$, $f_{\max}$ can be pushed up further much above f_{pl}.

In this paper we investigate experimentally an IJJ ratchet having the form of an asymmetric gear. The effect of coupling between IJJs, i.e., the mode of the fluxon motion, on the performance of the ratchet is studied.

A *periodic* potential for fluxons can be constructed by

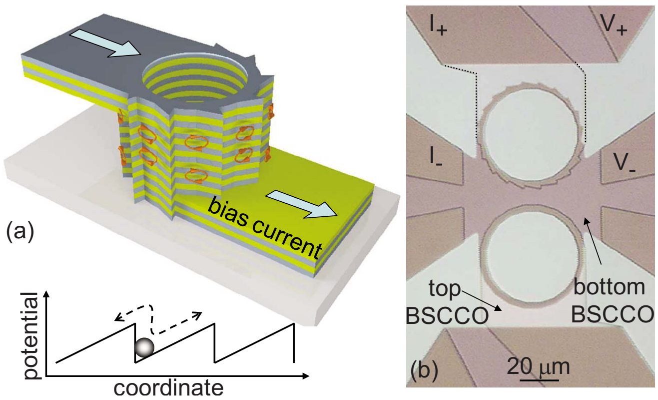

FIG. 1. (Color online) (a) A sketch of a superconducting gear with asymmetric teeth, consisting of six annular IJJs. Superconducting and insulating layers are dark (blue gray) and light (yellow), respectively. Josephson vortices are indicated by circulating supercurrents. The bias current is fed in via the upper electrode and is extracted via the lower electrode (arrows). The lower graph schematically shows the ratchet potential experienced by a fluxon. (b) Optical microscopic image with backside illumination of a chip shows two annular stacks (the gear and a smooth ring) consisting of 30 IJJs. $V_{\pm}$ and $I_{\pm}$ indicate voltage and current contacts to measure the gear. The contacts to the upper part of the gear are hardly visible and, therefore, its edges are shown by the dotted lines.

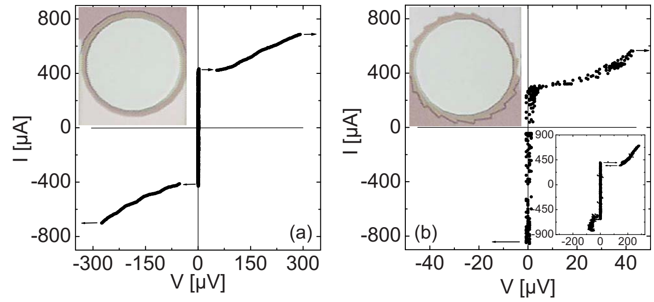

FIG. 2. (Color online) Current-voltage characteristics of (a) the smooth ring measured at $T=4.2$ K and (b) of the gear measured at $T=8$ K. Upper insets show optical images of the devices. Lower inset in (b) shows a different realization of fluxons trapped in the gear.

using an annular junction geometry. To make the potential *asymmetric* several techniques are available.[10] Since the potential energy is roughly proportional to the junction width at the location of the fluxon, below we use a saw-toothlike width variation along the circumference to construct an asymmetric potential, see Fig. 1(a). For the experiments, a piece of BSCCO single crystal (grown by a floating-zone method with a critical temperature $T_c \approx 88$ K) was patterned, by electron-beam lithography and argon-ion milling, into a ring standing on a big BSCCO pedestal. The following steps[26] are to glue the pattered structure onto another substrate, cleave it from the pedestal, and lithographically pattern it to form annular stacks of IJJs. Figure 1(b) shows the optical microscopic image of a chip containing two annular stacks with $N=30$ junctions, one of which is a gear with $n=20$ teeth and the other a smooth ring for comparison. The rings, with $L=157$ μm are enormously large in units of λ_J (~ 0.4 μm for BSCCO IJJs). We needed so large rings for the experiments since we not only wanted to investigate the ratchet effect by integral transport measurements but also characterize the sample by spatially resolved measurements of current distribution using low-temperature scanning laser microscopy (LTSLM). In principle, the rings can be made much smaller, having only a single period and the same value of L_1. Although the size of our gear is far from ultimate miniaturization, we expect the device to be fast—even assuming that the fluxons move at the lowest mode velocity c_N, f_{max} should be ~ 25 GHz.

To insert fluxons into the IJJ (Refs. 27–29) we pass a large bias current through the ring, producing self-heating of the structure to above T_c and simultaneously inducing a self-magnetic field. While resetting this current the stack returns to the superconducting state, trapping some number of fluxons.[30] Figures 2(a) and 2(b) show the *I*-*V* characteristics (IVCs) of a sample (a) without and (b) with teeth after trapping of vortices. The IVC of the smooth ring is symmetric with respect to the origin. For $I \approx 430$ μA Josephson vortices start flowing around the ring. At $I \approx 700$ μA the stack switches to the McCumber state (quasiparticle branch). In the flux flow state the maximum voltage $V_{\mathrm{max}}^{\mathrm{FF}} \approx 300$ μV. The IVC of the gear is strongly asymmetric, see Fig. 2(b). While at positive bias 300 $\mu\mathrm{A} < I < 570$ μA we observe a flux flow branch, at negative bias current $I=-850$ μA the sample switches directly to the McCumber state, indicating an effective pinning potential for clockwise vortex motion, see Fig. 1. For this particular cooldown (trapped vortices realization) $V_{\mathrm{max}}^{\mathrm{FF}} \approx 40$ μV [$V_{\mathrm{max}}^{\mathrm{FF}} > 200$ μV was observed for other cooldowns, cf., lower inset in Fig. 2(b)]. From the above values of $V_{\mathrm{max}}^{\mathrm{FF}}$, using the relation $V_{\mathrm{max}}^{\mathrm{FF}} = m\Phi_0 v_{\mathrm{max}}/L$, we can determine $mv_{\mathrm{max}} \approx 2.3 \times 10^7$ m/s for the smooth ring. Assuming that the fluxons move with the *lowest* mode velocity c_N, one estimates $m \approx 100$ as an upper limit for the number of fluxons. For the gear we find $m \approx 15$ for the realization presented in Fig. 2(b). For the realization shown in the inset of Fig. 2(b) $m \approx 90$. Thus, in most of the cases one traps only ~ 4 fluxons per junction and, thus, has very dilute fluxon configurations.

Nonetheless, another option to be discussed is that the observed branch is not due to moving fluxons but, e.g., caused by some junctions having switched to the quasiparticle branch (McCumber state). To obtain further information we have investigated the gear via LTSLM, see Ref. 31 for details. In brief, a laser beam (spot size ~ 2 μm^2) is scanned across the sample, locally increasing the temperature by 2–3 K. At the hot spot coordinates (x,y) the critical current density decreases and the quasiparticle conductance increases, giving rise to a change $\Delta V(x,y)$ in the total voltage serving as a contrast. Figure 3(a) shows an optical image of the gear taken by using the reflected light inside the LTSLM. The bright part in the optical image is from the gold layer underneath the BSCCO crystal. The teeth of the gear can be seen clearly. In the upper part they are hidden under the contacting electrode. When biased in the McCumber state, the voltage signal ΔV in the LTSLM image shown in Fig. 3(b) is negative and exhibits a shallow modulation in the upper part of the ring. ΔV is smaller at the lower part of the ring where

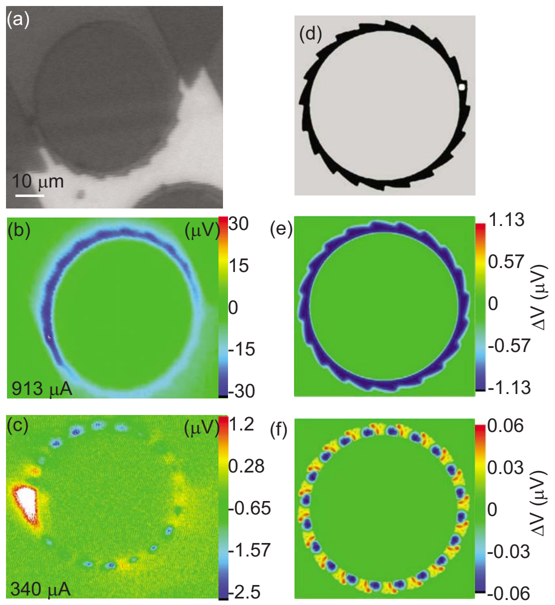

FIG. 3. (Color online) (a) Optical image of the gear. LTSLM images of IJJ biased (b) on the McCumber state and (c) on the flux flow branch. (d) The geometry used in simulations. The white dot is the "hot spot" of area $1.5\times 1.5\ \mu\text{m}^2$ (with 5% smaller critical current density and resistance), which is moved across the sample during the simulation. Simulated LTSLM images are shown for a bias (e) in the McCumber state and (f) on the flux flow branch.

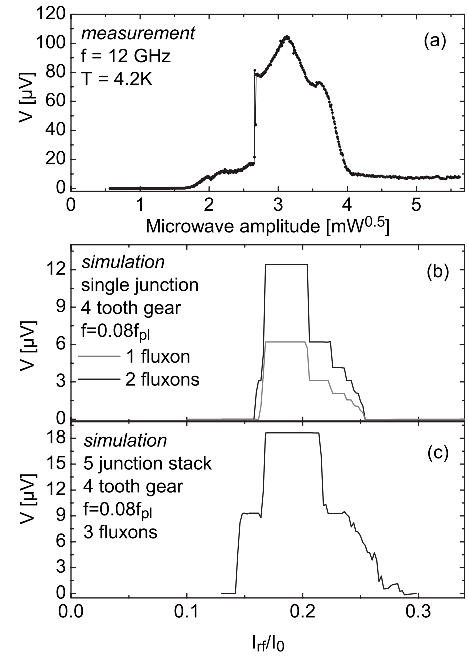

FIG. 4. (a) Measured rectified voltage V across the gear stack as a function of microwave amplitude of a 12 GHz drive at zero dc bias. (b) Simulated $V(I_{\rm rf})$ of a single junction containing one or two fluxons. (c) Simulated $V(I_{\rm rf})$ of a five junction stack containing two fluxons in layer 1 and one fluxon in layer 2. I_0 is the intrinsic critical current.

the Au layer provides additional cooling, lowering ΔT of the hot spot. The rather uniform distribution of ΔV along the circumference tells that the (quasiparticle) current flows fairly homogeneously across the ring. In contrast, a strong periodic modulation of the ΔV signal appears when the gear is biased to the flux flow state, see Fig. 3(c). Negative signals appear at the narrow parts of the junction. In between, ΔV is slightly positive. On the left side of the ring there is a single spot with positive ΔV, indicating a region with reduced critical current density. To simulate the LTSLM response, we have solved the two-dimensional (2D) perturbed sine-Gordon equation for the gear geometry used in the experiment and shown in Fig. 3(d). The simulations are done for a *single* junction. We calculated the response of only two adjacent teeth assuming one fluxon per tooth and replicated the signal along the 20 teeth gear. We assumed $\lambda_J=0.37\ \mu$m ($L_1/\lambda_J\approx 21$) and $f_{pl}=150$ GHz, yielding $c_s=3.5\times 10^5$ m/s. For the dimensionless damping parameter we used a value $\alpha=0.1$. Figures 3(e) and 3(f), respectively, show the calculated ΔV response in the McCumber state and in the flux-flow state just above the depinning current. These figures essentially reproduce the experimental results of Figs. 3(b) and 3(c). We are thus confident that we indeed observe the motion of fluxons at low bias currents.

To demonstrate rectification Fig. 4(a) shows the measured average dc voltage V of the gear vs microwave amplitude of a 12 GHz input drive. Above some threshold amplitude, a finite dc voltage appears. When the driving amplitude increases further, V also increases reaching a peak value $V_{\rm max} > 100\ \mu$V, which is three times as high as the one observed before.[12,14]

Assuming that all fluxons move with $v_{\rm max}=c_N$, one estimates $m\approx 40$, i.e., ~ 0.07 fluxons per tooth and per junction. One thus faces a diluted and, most likely, random fluxon arrangement which should be taken into account when comparing Fig. 4(a) with simulations. Figure 4(b) shows the calculated ratchet response of a four-tooth *single junction* gear containing either one or two fluxons. The calculations have been performed by using the 2D sine-Gordon equation with the same parameters as for the calculations of the LTSLM response. The drive frequency of $0.08f_{pl}$ corresponds to the 12 GHz used in experiment. One sees that the ratchet curves for the one- and two-fluxon cases are similar in shape and exhibit several constant voltage steps, the highest of which corresponds to the motion of the fluxon(s) by one tooth per ac cycle. Steps at higher drive amplitudes are fractional $1/k$ steps,[32] i.e., the fluxons move over one tooth per k periods of the drive. Single subharmonic steps were seen in earlier experiments[14] but not a sequence of them. A similar picture comes from the simulation of a $N=5$ junction stack with $n=4$ teeth as an example of a randomly trapped diluted vortex configuration, see Fig. 4(c). We expect that similar results can be obtained for the real geometry (which we cannot afford to simulate on reasonable time scales) but the steps will be smeared out for large N and m as in experiment.

While the size of the gear used in experiment was far from optimum, by numerical simulations one can study by how much the drive frequency can be increased. Simulating several stacks of up to nine IJJs we found a rectification up to $f_{\rm max}\sim 1.2 f_{pl}$ using $L_1/\lambda_J=4$. Thus, it seems that regardless of coupling between IJJs $f_{\rm max}$ is limited by f_{pl}, i.e., we did not succeed to excite the in-phase mode. $V_{\rm max}$ can be very high if a large N is used. Ideally, assuming a circumference $L=L_1 \approx 4\lambda_J$, with $f_{\max} \approx 1.2 f_{pl} \approx 200$ GHz, one finds $V_{\max} \approx N\Phi_0 f_{\max} \approx 40$ mV for $N=100$. Of course, in reality it will be hard to insert one fluxon into every junction. Even if this were possible, the fluxon-fluxon interaction may dominate over the interaction with the ratchet potential, resulting in a decrease in the ratchet effect. Finally, one could think of making use of the motion of regular fluxon lattices, e.g., moving in a rectangular configuration with the fastest mode velocity c_1. However, in such a configuration the fluxon size increases in the same manner as the mode velocity,[33] such that L_1 must be increased correspondingly to fit the fluxons. As a result the maximum ratio c_1/L_1 is unchanged and on the order of f_{pl}. So, the in-phase mode operation, even if achieved, will not bring advantages in terms of $f_{\max}$ and $V_{\max}$.

In summary, we have studied a gear-shaped fluxon ratchet based on stacked IJJs. Such a ratchet can have figure of merits that are well above the numbers feasible with Nb-based single junction devices. The advantages arise from a much higher Josephson plasma frequency and the possibility of stacking a large number of junctions. Although the 30 junction gear studied experimentally was far from optimum it already exhibited a rectified voltage $V_{\max} > 100$ μV at a drive frequency of 12 GHz. For an optimized device another order of magnitude appears possible in both the rectified voltage and the spectral bandwidth.

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