Nonreciprocal microwave transmission through a long Josephson junction

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We have measured the bidirectional propagation of microwaves through a long Josephson junction in a flux-flow regime. We demonstrate that the transmitted microwave power depends on the direction of microwave propagation with respect to the direction of the flux flow. This nonreciprocal behavior is explained by the interaction of the microwave signal with the moving fluxon chain inside the junction. Thus a long junction may act as an on-chip isolator for external microwave signals, with its transmission properties being fully controlled by the bias current and in-plane magnetic field.

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Nonreciprocal effects and time-reversal symmetry breaking are fascinating from the general point of view and also useful for various applications. One such application based on nonreciprocal properties is an isolator, a two-port device that transmits microwave or radio frequency power in one direction only. Isolators are used to protect microwave circuits on the input side against the conditions on its output side, for example, to prevent a microwave source from an unwanted signal reflected by a mismatched load.

Conventional isolators based on ferrites are rather bulky and expensive devices, but they are an integral part of nearly any precision microwave-based experiment. Recent breakthroughs in experiments with quantum microwaves at cryogenic temperatures revealed a clear need for compact, possibly on-chip, microwave isolators. This is a result of recent advances in superconducting qubit technology and rapid progress in circuit quantum electrodynamics.[1,2] Nonreciprocal components are required to suppress back-action from amplifiers and influence of a noisy environment on the sample under test. A possible approach toward nonreciprocal on-chip microwave circuits is using parametric modulation.[3] In this paper we present an alternative approach toward implementation of an on-chip isolator based on a long Josephson junction. Nonreciprocal performance will be demonstrated experimentally using a prototype device that is routinely fabricated in the standard thin-film niobium trilayer process common for most of Josephson junction circuits.

Ideas of using the flux-flow regime in long Josephson junctions for linear amplification have been discussed for decades,[4–7] but so far application niches for such devices are lacking. Generally speaking, nonreciprocal properties are common to any amplifier. A long Josephson junction in the flux-flow regime may act either as a microwave isolator or as a microwave amplifier due to interaction of the incident microwave with magnetic fluxons (Josephson vortices) moving inside the junction.

A long Josephson junction is set in the flux-flow regime by applying an external in-plane magnetic field and a bias current across the tunnel barrier, as sketched in Fig. 1(a). This regime is widely used in the flux-flow oscillators that have been developed over the past two decades for applications in superconducting submillimeter wave-integrated receivers.[8,9] Evidence of the emergence of the flux-flow regime was also obtained for high-T_c superconductors in the past decade.[10,11] The nonreciprocal response in the flux-flow regime is illustrated in Fig. 1(b). The intuitive idea here is that by choosing a specific direction of fluxon flow given by the combination of the polarities of the applied bias current and magnetic field, a preferred direction for the electromagnetic wave is created. The propagation is facilitated when the magnetic component of the applied electromagnetic wave modulates the magnetic field at the fluxon's entrance point into the junction. In contrast to this, the propagation is damped when the signal is applied to the fluxon's exit port in a long Josephson junction. Moreover, it is known from experiments[8,9] that the emission of a long

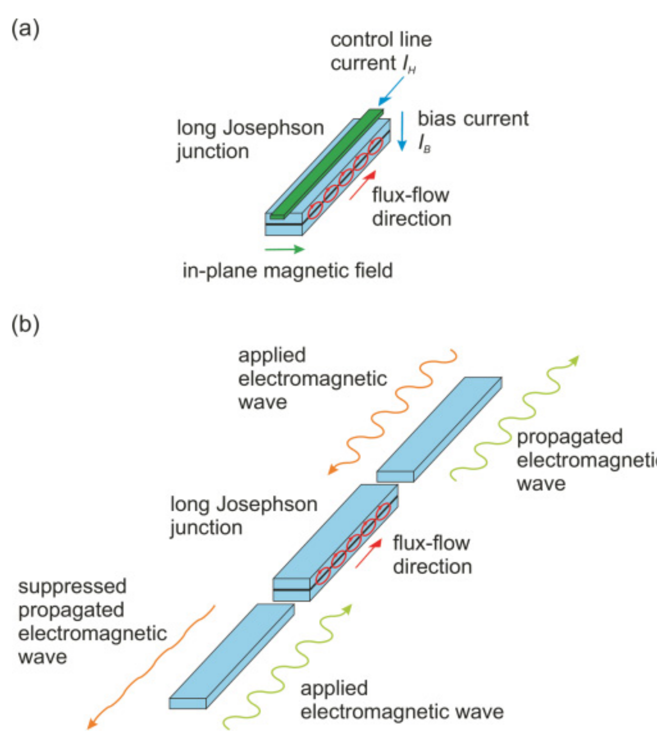

FIG. 1. (Color online) A long Josephson junction operates in the flux-flow regime as a nonreciprocal microwave device. The external microwave propagates along the direction of flux flow and is damped in opposite direction.

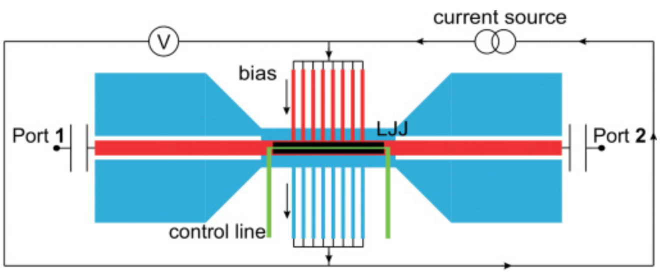

FIG. 2. (Color online) Schematic (dimensions not to scale) of the tested chip with a long Josephson junction embedded in a bicoplanar 10-GHz resonator placed between ports 1 and 2. Blue denotes the bottom metallization layer $M1$, which also serves as a ground plane; red is the top electrode layer $M2$ of the Josephson junction; green is the third niobium layer $M3$ used for the galvanically separated control line; and black depicts the area of the Josephson junction.

Josephson junction in the flux-flow regime at the frequency of the fluxon motion is negligible from the side of entering fluxons. For this reason the backaction of such a device can be neglected. The discussed isolation principle is pretty close to the working principle of traveling wave isolators proposed for the optical range.[12,13]

The 200-μm-long Josephson junction studied in our experiment was manufactured using the conventional niobium trilayer process with 1-kA/cm^2 critical current density.[14] The estimated Josephson penetration depth is $\lambda_J \simeq 11$ μm and the Josephson plasma frequency $\omega_p/2\pi \simeq 124$ GHz. The junction is placed in the middle of a bicoplanar half-wave resonator designed for $f_{\rm MW} = 10$ GHz (see Fig. 2). The function of the resonator is to improve the system's throughput by matching the long Josephson junction to the 50-Ω input. To fulfill the matching condition, the targeted quality factor of the resonator is chosen to be $Q_{\rm res} = \sqrt{50\,\Omega/Z_{\rm LJJ}}$, where $Z_{\rm LJJ}$ is the wave impedance of the junction and $Q_{\rm res}$ is defined by the choice of finger-shaped capacitors at the ends of the resonator. The external signal has the frequency $f_{\rm MW}$, which is much lower than the Josephson frequency $f_{\rm FF}$ of the flux flow. The external signal $f_{\rm MW}$ has to propagate through the junction as a modulation of the fluxon chain density. Some signal may bypass the long Josephson junction without direct interaction with the fluxons in the junction.

To measure nonreciprocal properties of our circuit, we have performed experiments at a temperature of $T = 4.2$ K. Two microwave cables with cold 20-dB attenuators were used to couple our device to the microwave source on port 1 (see Fig. 2) on one side and the spectrum analyzer on port 2 on the other side. Filtered dc lines were used to supply the bias current I_B and the current I_H through the control line generating an in-plane magnetic field. Typical voltage-current characteristics (IV curve) of the junction in the flux-flow regime are shown in Fig. 3(a). At a fixed value of the control line current of $I_H = 5.9$ mA, the current I_B was varied and simultaneously the power of the microwave signal transmitted through the junction was measured. At first, a microwave signal of $f_{\rm MW} = 10.2$ GHz was applied to one port and the microwave power was measured at the other port. Then we exchanged the microwave ports to reverse the propagation direction of the external signal. In this way, the propagation

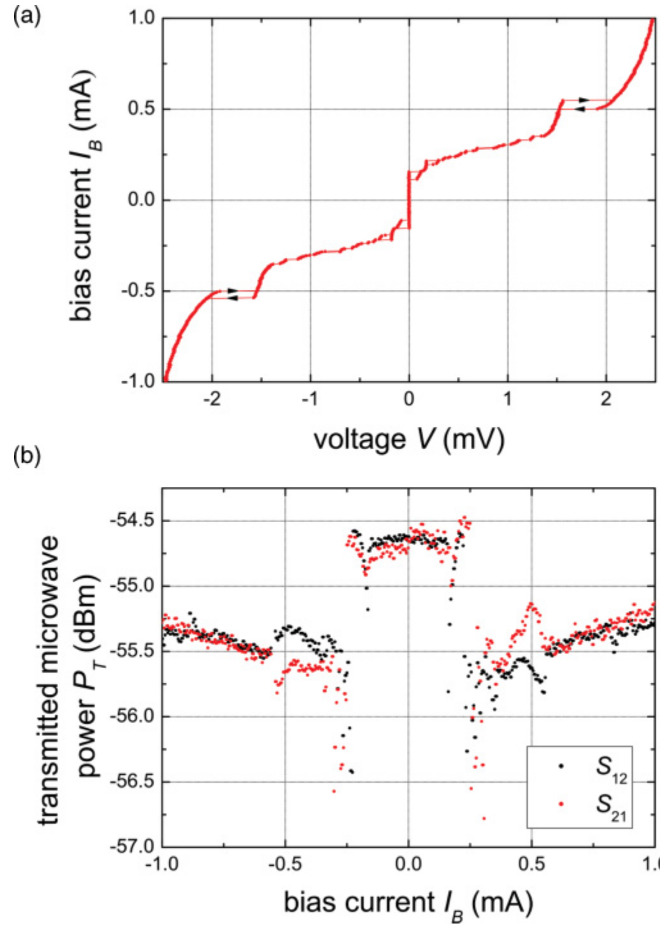

FIG. 3. (Color online) (a) Current-voltage characteristics of a long Josephson junction in the flux-flow regime. The magnetic field is generated by a control line current of $I_H = 5.9$ mA. Two large smooth voltage steps at about $I_B = \pm 0.5$ mA represent flux flow. (b) Transmitted microwave power at the frequency $f_{\rm MW} = 10.2$ GHz measured in the forward and backward directions versus bias current. In the region of flux-flow steps (at a bias current of approximately $I_B = \pm 0.5$ mA) a clearly distinguishable nonreciprocity is observed.

of microwaves was measured from right to left and then from left to right, which corresponds to S_{12} and S_{21} characteristics, respectively. The measured data are shown in Fig. 3(b). Comparing the transmission characteristics and the IV curve of the junction, peaks and dips in the transmission around the flux-flow steps can be seen at the bias values of $I_B \simeq 0.5$ mA. The difference in transmitted power P_T between the S_{12} and S_{21} traces at the same bias current gives the isolation value, which is a maximum of approximately 1 dB in this experiment. This relatively low isolation can be attributed to the saturation effect due to the large test signal since it was difficult to keep the signal-to-noise ratio large enough. It should be also mentioned that the flux-flow peaks on current-voltage characteristics like the one in Fig. 3(a) can be analyzed and well fitted by considering the Eck-Scalapino-Taylor model.[15] However, an adequate analysis of the interaction between the flux-flow mode and external microwave signal requires considering the junction's boundaries and therefore a full perturbed sine-Gordon equation with appropriate boundary conditions needs to be solved in order to describe our system.

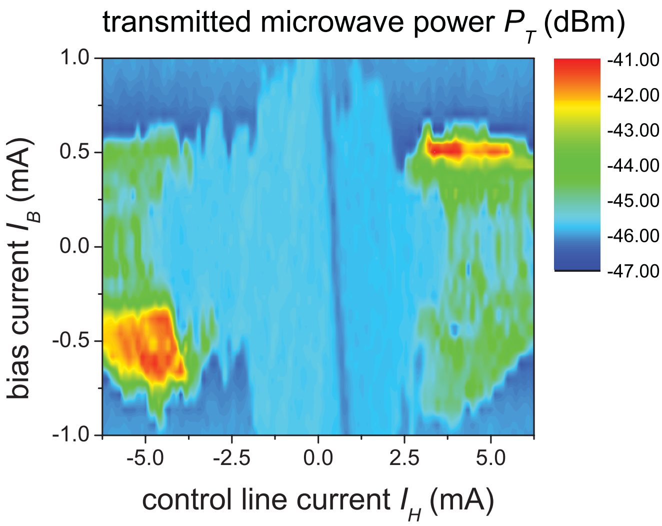

FIG. 4. (Color online) Transmitted microwave power of the $f_{\mathrm{MW}} = 10$ GHz signal through the long Josephson junction in the flux-flow regime. Red-orange regions correspond to an enhancement of the transmitted microwave power.

In the second series of experiments we added a low-noise cryogenic amplifier to the receiver side in order to improve the signal-to-noise ratio of the transmitted signal. This arrangement makes it impossible to measure S_{12} and S_{21} characteristics of the junction by swapping room temperature ports as described above. Nevertheless, we can characterize nonreciprocal microwave transmission simply by reversing the direction of the flux flow. This is done by reversing the polarity of either the in-plane magnetic field or the bias current of the junction. The transmitted microwave power P_T measured versus both the control line current I_H and the bias current I_B is shown using a color scale in Fig. 4. This measurement clearly reveals nonreciprocity. Microwave propagation is enhanced along the direction of flux flow, which is reflected by the red-orange spots in Fig. 4. The direction of the flux flow is reversed by altering the polarity of either the control line current I_H or the bias current I_B. In either case, the transmitted power is reduced. The asymmetry in the enhanced P_T in Fig. 4 appearing as different shapes of the two red spots is likely due to the stray magnetic field. The maximum isolation effect observed here is about 5 dB.

Qualitatively, the transmission of microwaves across a long Josephson junction in the flux-flow regime may be explained by a microwave-driven modulation of the local magnetic field at the flux entrance boundary of the junction. This time-dependent boundary field modulation causes a variation of the fluxon density in the moving fluxon chain.[16] The transmission of low-frequency microwave signal is due to density variations in the propagating fluxon chain. The fluxon velocity at the entrance port of the junction is significantly lower than at the junction exit port. Fluxons are accelerated along the junction by the Lorentz force up to their maximum velocity, which is close to the Swihart velocity. The microwave signal is transmitted due to interaction between neighboring fluxons in the moving chain, which in turn depends on the chain velocity. The repulsive interaction between adjacent fluxons gets renormalized according to their length dilatation relative to the Swihart velocity and their relativistic mass changes accordingly. Thus, at the junction exit port the density of Lorentz-contracted fluxons in their reference frame is effectively smaller than it is in the junction entrance region and the fluxon mass is correspondingly much larger. Both of these effects make modulation of the fluxon chain density by a microwave signal applied at the at the junction exit port very inefficient. It can be also argued that, in the case of ideal impedance matching, the isolation value $S_{21} - S_{21}$ for external microwave signal propagating through the long Josephson junction biased in flux-flow regime should be related to the ratio between flux-flow emission power at the fluxon exit port of the junction P_{FFO} to the flux-flow power emitted back to the junction exterior from the fluxon entrance port P_{back}. From experiments with impedance-matched Josephson flux-flow oscillators it is known that P_{back} is several orders of magnitude smaller than P_{FFO}.[8,9]

There are several ways to improve the nonreciprocal properties of the proposed circuit, which can be measured through the isolation value. The simplest option is to increase the length of the long Josephson junction. The isolation value should increase up to the junction size approximately equal to the fluxon acceleration length ℓ_a, which depends on the loss coefficient inside the junction. An alternative approach is to avoid as much as possible reflections of the external microwave signal by improving the impedance match between the microwave input port and the long Josephson junction impedance Z_{LJJ}. In the reported circuit the matching is facilitated by a bicoplanar resonator embedding the junction (Fig. 2). Such a matching network may not be optimal for a distributed Josephson junction, which is supported by the rather low experimentally measured isolation value. It should be possible to improve impedance match by either using a lower impedance value for all on-chip lines or developing a high-impedance long-junction structure. The first issue is concerned with the fact that a 50-Ω standard is not a real necessity for on-chip lines. The second point would require implementing the long junction in the form of a discrete Josephson transmission line (parallel array of small junctions). However, simple estimates show that making $Z_{\mathrm{LJJ}} = 50\ \Omega$ would require submicrometer small junctions and thus the usage of electron beam lithography for fabricating the circuit.

In summary, we have demonstrated here the nonreciprocal transmission of a microwave signal through a long Josephson junction. The transmitted microwave power is enhanced when the propagation direction of electromagnetic wave coincides with the direction of the flux flow. In contrast, the transmission is suppressed when the propagation directions are opposite each other. Maximum isolation achieved in the presented experiments is 5 dB in a bandwidth of approximately 0.5 GHz. The observed nonreciprocity is explained by the interaction of the external microwave signal with a chain of fluxons moving in the junction. The observed properties can be employed for a realization of cryogenic on-chip microwave isolators and circulators.

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