Fluxon threshold properties on a resistively coupled Josephson transmission line

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Fluxon threshold properties on a resistively coupled Josephson transmission line

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Fluxon threshold properties between transmission and nontransmission have been investigated with regard to a resistively coupled Josephson transmission line (RCJ). The RCJ consists of two Josephson transmission lines (JTL's), which are Nb/Nb-oxide/Pb junctions, interconnected by an Au series resistor. Whether an incident fluxon transmits or not at the coupling resistor depends on the input pulse height and the bias current levels for the two JTL's.

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It is well known that a quantized flux (fluxon) propagates in a Josephson transmission line (JTL) as a solitary wave (soliton), because a JTL can be described by the sine-Gordon type equation. Many applications of JTL's, based on the employment of a fluxon as an information bit, have been proposed. In particular, resistively coupled JTL's are attractive for the following reason. Transmission and annihilation of an incident fluxon can be controlled by the resistor, where flux quantized condition does not hold. However, the threshold properties have not yet been investigated with regard to a resistively coupled JTL (RCJ) experimentally. Theoretical approaches have also been limited only to numerical simulations, because, near the coupling resistor, the single fluxon waveform cannot be described by a one-kink solution of the sine–Gordon equation.

In this letter, the threshold properties for an RCJ have been investigated using the measuring system for observing a single fluxon. An RCJ, which consists of two JTL's interconnected by a series resistor, has been fabricated by conventional fabrication techniques.

The fabricated RCJ structure is shown in Fig. 1. JTL1 and JTL2 (25-μm width and 5-mm length), which are Nb/Nb-oxide/Pb junctions, are interconnected by a series Au resistor \( R_c \). Figure 2 shows an equivalent circuit. The input and output ends are terminated by Au resistors \( R_T \). Both bias currents \( I_{B1} \) and \( I_{B2} \) are homogeneously supplied by comblike electrodes.

**FIG. 1.** Fabricated RCJ structure representing Nb/Nb-oxide/Pb junctions and Au coupling resistor \( R_c \). Input and output ends are terminated by Au resistors \( R_T \).

**FIG. 2.** Equivalent circuit of fabricated RCJ.

The following characteristics were measured from the JTL1 and JTL2 bias electrodes. *I–V* characteristics for the JTL1 were almost the same as for the JTL2. Maximum Josephson current density is determined to be \( j_c = 4.8 \text{ A/cm}^2 \). Josephson penetration depth and plasma period were estimated at \( \lambda_j = 205 \mu \text{m} \) and \( \tau_j = 24 \text{ ps} \), respectively. Damping coefficient (associated with quasiparticle tunneling loss) is estimated at \( \alpha = 0.0036 \), using the linear portion of monitor junction *I–V* characteristics around the origin.

In order to determine the \( R_c \) and \( R_T \) values, different *I–V* characteristics were also measured, using data gleaned from the respective Nb electrodes of both JTL's. Their normal resistance value corresponds to \( 2R_T R_c/(R_c + 2R_T) \). On the other hand, the normal resistance component for the JTL1 is given by \( (R_c + R_T)R_T/(R_c + 2R_T) \). By using the above relations, the coupling resistor and termination resistors were estimated at \( R_c = 0.83Z_0 \) and \( R_T = 0.46Z_0 \), where \( Z_0 = 0.056 \Omega \) is the characteristic impedance of the present JTL's. This method is rather exact because the \( R_c \) and \( R_T \) values are much smaller than the subgap resistance value of the JTL's.

Output voltage responses at the output termination resistor were measured at the moment when voltage pulses were fed to the input termination resistor. Figure 3 shows the input voltage waveform at attenuation 0 dB and observed waveform examples with fixed bias currents \( I_{B1} = I_{B2} = 2.5 \text{ mA} \) (normalized bias \( \gamma_1 = \gamma_2 = 0.42 \), \( \gamma_1 = I_{B1}/I_{c1}, \gamma_2 = I_{B2}/I_{c2} \), where \( I_{c1} \) and \( I_{c2} \) are maximum Josephson currents for the JTL1 and JTL2, respectively). Actual input pulse height is reduced due to a mismatch factor \( 2Z_0/50 \). With a decrease in input pulse height, the number of output fluxons was also decreased and none was observed below \(-24 \text{ dB} \). The observed waveforms indicate that output fluxons are not completely dissociated. At \(-12 \text{ dB} \) (input height 141 mV) the output waveform is thought to
FIG. 3. Observed output waveform examples, as a function of input pulse height with fixed bias \( \gamma_1 = \gamma_2 = 0.42 \).

include more than four fluxons. The waveform at \(-20\) dB, however, corresponds to a single fluxon. These observed features seem to be caused by the high bias and low damping condition \((\gamma_1 = \gamma_2 = 0.42\) and \(\alpha = 0.0036\)), where propagated fluxons are very steep and bunched together.\(^8\)

The waveform profiles are shown in Fig. 4 as a function of bias current levels for the two JTL's. By decreasing both bias levels with fixed input height of \(-12\) dB, the output fluxon number decreases. At \(\gamma_1 = \gamma_2 = 0.17\), a single fluxon was observed. However, propagation delay times mostly do not change. The propagated fluxon abruptly disappears below \(\gamma_1 = \gamma_2 = 0.08\).

With regard to the ordinary JTL,\(^9\) the fluxon was propagated even at \(\gamma = 0\) and input of 38 mV. In that JTL, the propagation delay time gradually increased with a decrease in the bias level. On the contrary, in the present RCJ, the fluxons abruptly stopped propagating below some bias levels. This result indicates that an incident fluxon annihilates or is reflected as an antifluxon at the coupling resistor \(R_C\).

Investigation was made to determine the threshold properties between the transmission and nontransmission as a function of the two bias current levels \((\gamma_1, \gamma_2)\). The results are shown in Fig. 5. In this figure, the broken line shows the boundary beyond which the JTL's switched to the voltage state. Open circles, triangles, and squares indicate that incident fluxons pass through the coupling resistor at \(-20\), \(-16\), and \(-12\) dB input pulses, respectively. Filled symbols indicate nontransmissions. Note that, in the present experiments, it could not be observed whether incident fluxon reflections occur or not at the coupling resistor \(R_C\).

The threshold properties depend on the input pulse height and respective bias levels. For the higher input case, propagated fluxons were observed, even at the lower bias levels. The previous report\(^9\) showed that the propagated fluxon number increases and the interval times between the respective fluxons decrease as the input pulse height increases. Therefore, for the higher input case, it is expected that more effective input energy would be fed into JTL2 for fluxon formation. This causes the input pulse height dependence.

In the higher \(\gamma_1\) case, the incident fluxons pass through the coupling resistor, even at the lower \(\gamma_2\) level. By decreasing the \(\gamma_1\) level, higher \(\gamma_2\) feeding is required for fluxons to pass through. These bias dependences are explained in the following terms: in a mechanical analog\(^2\) a fluxon is equivalent to a \(2\pi\) rotation of pendulum arrays. The bias current provides pendulums external torque density. High \(\gamma_1\) increases the fluxon energy, which is fed into the JTL2 input.

These observed properties are qualitatively foreseen as functions of coupling resistance.\(^2\) The present experiment actually shows that transmission and nontransmission of an incident fluxon at a coupling resistor can be easily controlled by both external bias current levels. Fluxon control ability is realized by the release from the flux quantized condition at the coupling resistor, which enables fluxons to annihilate.

To compare the experimentally obtained results with...
simulated results, the following modified sine–Gordon equation
is numerically integrated with a real input wave form and experimentally obtained JTL parameters:
\[ \phi_{xx} - \phi_{tt} = \sin \phi + \alpha \phi_t - \beta \phi_{xxx} - \gamma. \]
In numerical simulations of the present RCJ, the boundary can be described by \( \phi_{2t} = \phi_{1t} + R_c \phi_{1x} \) and \( \phi_{2x} = \phi_{1x}, \)
where \( \phi_t \) and \( \phi_x \) indicate the phase differences for JTL1 and JTL2 on both sides of the coupling resistor, respectively. The
rf loss coefficient \( \beta \) is assumed to be 0.028, according to Ref. 9. In Fig. 5 the dotted line represents the numerical results
obtained at -20 dB input. The dependences of bias levels qualitatively agree with experimental results, if the effective
input pulse is assumed to be at -14 dB. The difference in input pulse height between the experiments and simulations
is thought to be due to the existence of stray resistance between the Nb pad and spring contact, through which the
input pulse is fed. However, all of the discrepancy cannot be attributed to the stray resistance for the following reasons.
The stray resistance value corresponds to about 50 \( \Omega \), which is much larger than the usually obtained amount. In the other
input cases, at -16 dB and -12 dB, the threshold properties, however, could not be explained by using a simple
assumption of a 6-dB difference in the input pulse heights. It
was also shown, by simulations that the inductance compo-
nent effect at the coupling resistor was negligible. This discrepancy will be a factor for future study.

In summary, fluxon threshold properties have been investigated on a resistively coupled Josephson transmission line. Whether an incident fluxon transmits or not at the coupling resistor depends on both bias levels and input pulse height.

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