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Tunable oscillator using pulsons on large-area lossy Josephson junctions

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A tunable resonator in the gigahertz-range using circular sine-Gordon fluxons or pulsons on a lossy large-area Josephson junction with a circular impurity in the Josephson current density is proposed. To obtain steady tunable oscillations in a lossy medium, one must supply energy ("negative" resistance). We propose to control the constant bias current with an autonomous pulson velocity-sensitive switch. One possibility for fine tuning the oscillations is to vary the strength of the Josephson impurity current.

PACS numbers: 85.25. + k, 74.50. + r

Application of sine-Gordon fluxons on a Josephson junction transmission line has been proposed by McLaughlin and Scott[1] for an electromagnetic oscillator in the submillimeter range. In the present letter we also propose a *tunable* oscillator however, based on the unique dynamical behavior of circular "fluxons" on lossy large-area Josephson junctions with current bias and inhomogeneities in the Josephson current. In a numerical study Bogolyubskii and Makhankov[2] found that such fluxons collapse and expand in an oscillatory motion before the energy is radiated. They named these fluxons "pulsons." Christiansen and Olsen[3] studied their motion in detail and have analyzed the expansion and the return effect by perturbation methods.

In the present work we use three *new* properties of pulsons discovered by detailed numerical simulation; namely (i) a constant current bias in a prescribed range controls the radial pulson velocity, u ($|u| < 1$), without producing noticeable continuum radiation. (ii) A pulson will undergo "specular" reflection from a smooth azimuthally symmetric impurity in the Josephson current density. (iii) In a lossy medium, no constant value of bias will produce a permanent oscillation. The radial motion of the pulson as a result of (i)–(iii) can be interpreted as a "ballistic" motion. As discussed below, in a lossless medium these properties are sufficient to obtain a tunable oscillation. However, in a lossy medium one must introduce *a switching of current bias*: that is, when the pulson is expanding ($u > 0$), the bias is switched to a larger constant magnitude. For example in a strongly damped junction ($Q \sim 10$) we have obtained angular frequencies Ω in the range 10–25 GHz, where $\Omega = 66.5\,\omega$ GHz, and ω is the normalized frequency[4] used below.

The magnetic flux ϕ on a large-area Josephson junction satisfies the dimensionless equation[4]

$$\Delta\phi - \phi_{tt} - j\sin\phi = \alpha\phi_t + \gamma. \tag{1}$$

We assume azimuthal symmetry where $\Delta = \partial^2/\partial r^2 + r^{-1}\,\partial/\partial r$ and the Josephson current density $j = j(r)$. The term $\alpha\phi_t$, where α is a constant, represents the dissipation due to tunneling of normal electrons across the barrier. The spatially uniform current bias γ provides input energy to the junction.

For a lossless medium ($\alpha = 0$) Fig. 1 shows results of a detailed numerical simulation[3] displayed in terms of ϕ_r. The Josephson current and the initial conditions were chosen as

$$j(r) = 1 + a\,\mathrm{sech}^2(r - R_1), \tag{2}$$

$$\phi(r,0) = 4\tan^{-1}\exp(r - R_0), \tag{3}$$

$$\phi_t(r,0) = 0,$$

where the initial conditions imply a pulson velocity $\dot{R}(0) = 0$. We see the pulson falls towards the origin. At the impurity ring it is "specularly" reflected. The expanding pulson behaves as if in homogeneous medium and returns.

Information from several runs is summarized in Fig. 2 as the trajectory $r = R(t)$, where ϕ_r has a maximum [that is, $\phi(R(t),t) = \pi$] and pulson amplitudes $\phi_r|_{r=R}$. We observe a tunable oscillation in the range $-0.24 \leqslant \gamma < \gamma_c \simeq 0.0637$ and escape for $\gamma > \gamma_c$.

For all positive values of γ we observe a high-frequency modulation in the pulson amplitude shown in Fig. 2(b). The oscillating pulson amplitude is slightly distorted ($\gamma = -0.08$) due to radiation emission in connection with reflection and return events. However, the amplitude of the pulson did not decrease, within our present computational accuracy, during the seven periods of case $\gamma = 0$ or the nine periods of case $\gamma = -0.08$. To obtain a lower bound on Q due to this radiation, requires longer simulation runs of higher accuracy.

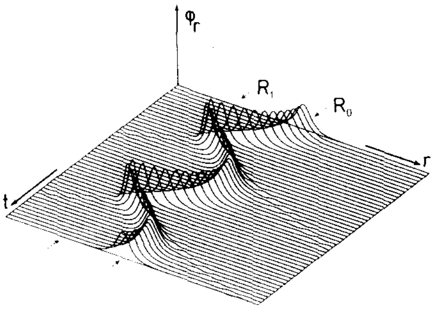

FIG. 1. Numerical simulation of oscillating pulson, $\phi_r(r,t)$, in lossless medium without bias ($\alpha = \gamma = 0$). The impurity is given by (2) with $a = 5$ and $R_1 = 15$. In the initial condition (3) the radius $R_0 = 25$.

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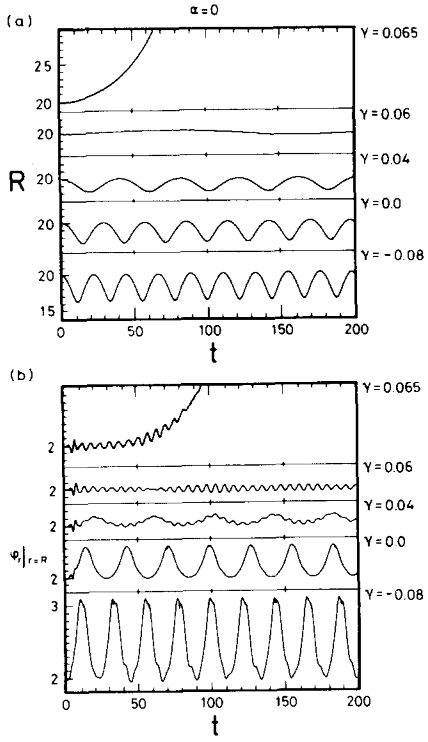

FIG. 2. Pulson behavior in a lossless medium for different bias values ($\gamma = -0.08, 0, 0.04, 0.06$, and 0.065). (a) Trajectories, $r = R(t)$, for $\phi_{r,\max}$. (b) Pulson amplitudes defined by $\phi_r(R(t),t)$. Parameters in (2) and (3) are $\alpha = 0$, $a = 5$, $R_1 = 15$, and $R_0 = 20$.

In Table I the oscillation frequency ω is given for various values of γ. The best straight line fit yields $d(\omega/\omega_{\mathrm{av}})/d\gamma = -2.61$. We have found that the oscillation period depends weakly on the magnitude of the Josephson current inhomogeneity [a in (2)], thus providing a possible approach to fine tuning. That is, the larger a, the more impenetrable is the barrier to inward pulson motion and the quicker is the reflection. For example, if one doubles a in Eq. (2), the frequency increases by 11%. We are presently conducting a detailed study of these phenomena.

We now discuss basic results of a perturbation analysis. The Hamiltonian for the pulson given by (1)

$$H = 2\pi\int_0^\infty \left[\tfrac{1}{2}\phi_r^2 + \tfrac{1}{2}\phi_t^2 + j(1-\cos\phi\right|\, r\,dr \tag{4}$$

satisfies the differential equation

$$\frac{dH}{dt} = -2\pi\int_0^\infty \phi_t(\gamma + \alpha\phi_t)r\,dr. \tag{5}$$

We then approximate the pulson by

$$\phi(r,t) = 4\tan^{-1}\exp[(r-R)/(1-\dot{R}^2)^{1/2}], \tag{6}$$

where R is the radius of the pulson defined by $\phi[R(t),t] = \pi$. The radial velocity u then equals $\dot{R}$.

TABLE I. The pulson oscillation frequency ω as a function of the constant bias γ in a lossless ($\alpha = 0$) large-area Josephson junction described by Eq. (1).

γ	-0.24	-0.16	-0.08	-0.04	0.0	0.04
ω	0.38	0.31	0.28	0.26	0.22	0.15

In the case $\alpha = \gamma = 0$ we get[5]

$$16\pi Rj(R)/(1-\dot{R}^2)^{1/2} \simeq H_0, \tag{7}$$

where H_0 is a constant. With (2) and $\dot{R}$ from (7) it can be shown that $\min R \equiv R_2 \leqslant R(t) \leqslant R_0 \equiv R(0)$ with oscillation period T_0, where

$$R_2 = R_0[1 + a\,\mathrm{sech}^2(R_0 - R_1)]^{1/2},$$

$$T_0 = 2\int_{R_0}^{R_2} dr\,\{1 - r^2[1 + a\,\mathrm{sech}^2(r - R_1)]/R_2^2\}^{-1/2}. \tag{8}$$

Letting $R_0 = 20$, $R_1 = 15$, and $a = 5$, we get $R_2 = 16.9$ and $T_0 \simeq 26$ [obtained numerically from (8)]. The corresponding simulation values are $R_2 \simeq 17.2$ and $T_0 \simeq 28$. The ballistic concept can be explained in terms of Eq. (7).

In the case $\gamma \neq 0$, $j \equiv 1$, and $\alpha = 0$ and the assumption (6), (3), and $R_0 \gg 1$, perturbation methods yield $R(t) = R_0 + A(R_0,\gamma)t^2$, where $A = -0.88\,R_0^{-1}$ for $\gamma = 0$ and $A = 0$ for $\gamma = \gamma_c = (4/\pi)R_0^{-1}$. For $\gamma > \gamma_c$ we find $A > 0$, indicating escape of the pulson. This is the reason for the ballistic analogy—A is proportional to the acceleration of a particle in a gravitational field.

On a lossy large area Josephson junction ($\alpha > 0$) we get damped oscillations or escape of the pulson (for $\gamma > \gamma_c$). To overcome damping we introduce the *concept* of an autonomous current-bias switch. That is, when $u < 0$, we set $\gamma = 0$, and when $u > 0$, we set $0 < \gamma_0 < \gamma_c$. The results in Fig. 3 for $\alpha = 0.02$ (Ref. 6) show that if γ_0 is too small (0.005), the oscillation is still damped. For larger valyes of γ_0 (0.015) we get persistent oscillations with a frequency $\omega = 0.21$, corresponding to an angular frequency 14.0 GHz.

If γ_0 is increased, we obtain a decrease in frequency in accordance with the ballistic analogy. This is shown for $\gamma_0 = 0.030$, where a steady-state frequency, $\omega \simeq 0.11$, is obtained at approximately $t = 600$. Thus

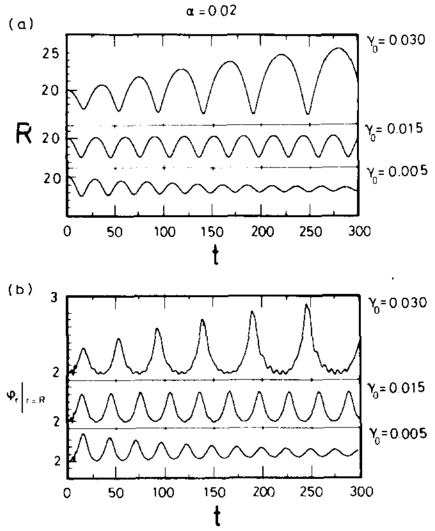

FIG. 3. Pulson behavior in a lossy medium with velocity sensitive current-bias switch. (For $u < 0$: $\gamma = 0$, for $u > 0$: $\gamma = \gamma_0 = 0.005, 0.015$, and 0.030). (a) Trajectories, $r = R(t)$, for $\phi_{r,\max}$. (b) Pulson amplitudes defined by $\phi_r(R(t),t)$. Parameters in (2) and (3) are $\alpha = 0.02$, $a = 5$, $R_1 = 15$, and $R_0 = 20$.

$d(\omega/\omega_{av})/d\gamma_0 = -41.7$. If α is reduced, we observe persistent oscillations with higher frequencies. Furthermore, we have also obtained a frequency-modulated signal by varying γ_0 sinusoidally in time. This phenomenon occurs because of the rapid response of the Josephson junction.

We have presented a way for obtaining coarse- and fine-tuned oscillations in the gigahertz range in a lossy large-area Josephson junction based on pulson dynamics. One method for controlling the energy supplied to the oscillating pulson is studied, namely an autonomous pulson velocity-sensitive curent-bias switch.

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Identification of quench origins in a superconductor with acoustic emission and voltage measurements

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The acoustic emission and voltage measurements were used to identify quench sources in a current-carrying superconductor. The sources identified were (i) conductor motion, (ii) epoxy cracking, and (iii) pure joule heating resulting from the conductor reaching critical current. The combination of these two techniques appears to be a promising diagnostic tool in probing premature quenches in superconductors and superconducting magnets.

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It is widely accepted that mechanical disturbances, particularly abrupt ones, are the major causes of premature quenches in high-current density, tightly-wound, adiabatic superconducting magnets. The mechanical disturbances arise in the magnet winding due to the Lorentz-force stresses induced during the magnet energization. The abrupt disturbances appear chiefly in the form of conductor motion and mechanical imperfections of the substructure such as epoxy cracking and debonding.

Voltage measurement is a universally used technique in monitoring magnets. However, because a voltage may be resistive, inductive, or a combination of the two, and since only the inductive voltage may result, though not necessarily all the time, from some mechanical motions in the presence of a flux, voltage measurement alone is not generally sufficient to identify the cause of a premature quench. Indeed in the present experiment we recorded many instances where voltage spikes were observed without the simultaneous occurrence of acoustic emission (AE) events. These voltage spikes, we concluded, were not associated with abrupt conductor motions.

In a recent study of acoustic emission in superconductors,[1] we have found that acoustic signals are chiefly generated by conductor motion. An equally important additional finding has been that other probable AE sources such as flux motion are insignificant compared with conductor motion. (Abundant acoustic signals were found to be generated during a flux jump; this is a moot point when considering multifilamentary superconductors because of the absence in the conductors of flux jumping.)

In this letter we report results of a quench-current experiment on a short length of a high-current density superconductor. Both voltage and AE signals were measured in the experiments; this dual voltage/AE measurement technique was first used by Turowski[2] in his investigation of training in superconducting magnets. Using combined results of these two measurement techniques, we have classified quenches into three groups and identified a probable source of quench for each group.

The experiment used an "Isabelle" braid, the conductor for the beam-handling magnets for the Brookhaven National Laboratory's colliding-beam project, Isabelle.[3] The braid, 0.8 mm thick and 17 mm wide, contains 97 copper composite multifilamentary NbTi strands, each strand 0.3 mm in diameter.

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