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Using Josephson vortex lattices to generate, detect and control THz radiation

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Abstract

We propose several devices to generate, filter, and detect THz radiation using strongly anisotropic layered superconductors, such as $Bi_2Sr_2CaCu_2O_{8+\delta}$. (1) We show that a moving Josephson vortex (JV) in spatially modulated layered superconductors generates out-of-plane THz radiation. Remarkably, both the magnetic and in-plane electric fields radiated are of the same order, which is very unusual for any good-conducting medium. Therefore, the out-of-plane radiation can be emitted to the vacuum without the standard impedance mismatch problem. (2) We show that JV lattices can produce a photonic band gap structure (THz photonic crystal) with easily tuneable forbidden-frequency zones controlled by the in-plane magnetic field. The scattering of electromagnetic waves by JVs results in a strong magnetic-field dependence of the reflection and transparency. These proposals are potentially useful for controllable THz filters. (3) We predict the existence of surface waves in layered superconductors in the THz frequency range, below the Josephson plasma frequency ω_J. These predicted surface Josephson plasma waves can be resonantly excited by incident THz waves, producing a huge enhancement of the wave absorption. This effect could be used for new THz detectors.

Keywords: Vortex dynamics; Photonic crystals; Surface waves; Josephson plasma waves; THz radiation of Josephson vortex

1. Introduction and summary of our results

It has been recognized (see, e.g., [1,2]) that the Josephson plasma frequency ω_J of Josephson plasma waves (JPW) [3,4] lies in the otherwise hardly reachable THz range, with potentially important scientific and technological applications. A grand challenge is to controllably generate, filter or detect electromagnetic waves in $Bi_2Sr_2CaCu_2O_{8+\delta}$ and other layered superconducting compounds because of its Terahertz frequency range.

For filtering THz waves, tunable filters of THz radiation have been proposed [5] using the Josephson vortex lattice as a tunable photonic crystal. Indeed, the Josephson vortex (JV) lattice is a periodic array that scatters electromagnetic waves in the THz frequency range. We show that JV lattices can produce a controllable photonic band gap structure [5,6] (THz photonic crystal) with easily tunable forbidden zones controlled by the in-plane magnetic field. The scattering of electromagnetic waves by JVs results in a strong magnetic-field dependence of the reflection and transparency. Fully transparent or fully reflected frequency windows can be conveniently tuned by the in-plane magnetic field.

Our suggested design for novel THz detectors [7] employs the predicted surface Josephson plasma wave, which can propagate along the superconductor–vacuum interface when the wave frequency is below ω_J. We derive that the incident THz wave can resonantly excite the surface

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wave at certain angles between the incident wave and the sample surface. This results in a strong increase of absorption of THz wave in the sample and resonant peak of the sample resistance. The position of the peak allows to measure frequency and direction of the incident THz wave.

Considering recent advantages in sample fabrication [8,9], we also propose [10] several experimentally realizable devices for generating THz radiation using periodically modulated layered superconductors. Below, we discuss this novel class of superconducting THz emitter in more detail.

2. Out-of-plane THz radiation to solve the impedance mismatch problem

For electromagnetic waves in any conducting media, the electric field E is very weak with respect to the magnetic field H: $E \ll H$. Also, for in-plane radiation: $E \ll H$. Thus, only a small fraction (about E/H) of the radiation can leave the sample. This is the so-called "impedance mismatch" problem that has severely limited progress in this field for years. Now, we are also considering c-axis short-wavelength out-of-plane radiation. This radiation has a strong enough in-plane electric field $E_{\parallel}$ to overcome the superconducting–vacuum interface. Indeed, $E_{\parallel}$ and the magnetic field both are of the same order of magnitude, similar to the one for waves propagating in the vacuum. This solves the impedance mismatch problem.

The out-of-plane JPW can be emitted, for instance, by a fast moving Josephson vortex if its velocity V exceeds a certain threshold value $V_{\min}$. However, this out-of-plane Cherenkov-type radiation always completely reflects from the sample boundary and thus cannot be emitted into the vacuum. Indeed, the longitudinal wave vector q for the Cherenkov radiation is related to the wave frequency ω by $q = \omega/V$ and is much larger than the maximum possible value ω/c for waves in vacuum. This problem can be solved if the out-of-plane Cherenkov radiation propagates through a modulated layered superconductor. The out-of-plane Cherenkov wave interacting with periodic inhomogeneities generates new modes with wave vectors $q_m = q - 2\pi\, m/a$, where a is the spatial period of the modulations and m is an integer. Thus, the wave vector $q_1 = q - 2\pi/a$ can meet the condition $q_1 < \omega/c$ for vacuum waves and is emitted from a sample without an impedance mismatch.

3. Non-local Sine-Gordon equation for moving Josephson vortex in a layered superconductor

Besides potential applications to THz technology, the motion of a JV in layered superconducting materials has significant scientific interest because it can mimic some properties of fast relativistic particles. Indeed, it is well-known [11] that the Sine-Gordon equation, describing the motion of a JV in a conventional Josephson junction, is invariant under a Lorentz transform, where the speed of light is replaced by the Swihart velocity [11]. For a standard Josephson junction, the Swihart velocity restricts both the maximum speed of small magnetic field perturbations and the maximum vortex velocity.

In layered structures, the equation describing the Josephson vortex and its magnetic field $H(x,y,t)$ becomes nonlocal [10]:

$$\begin{aligned} &H - \lambda_{ab}^2 \partial^2 H/\partial y^2 - \lambda_c^2 \partial^2 H/\partial x^2 \\ &\quad - \omega_{\mathrm{J}}^{-2} \partial^2/\partial t^2 (1 - \lambda_{ab}^2 \partial^2/\partial y^2) H = 0; \\ &\omega_{\mathrm{J}^*}^{-2} \partial^2 \phi/\partial t^2 + \sin\phi = (l/\pi) \int \mathrm{d}\zeta K_0(\mid x - \zeta \mid /\lambda_c) \partial^2 \phi/\partial^2 \zeta; \\ &\partial^2 \phi/\partial x^2 = 2\pi \lambda_{ab}^2/\Phi_0 \{\partial H(y=+0)/\partial y - \partial H(y=-0)/\partial y\}. \end{aligned} \tag{1}$$

Here, the Josephson plasma frequency $\omega_{\mathrm{J}}/2\pi$ is about 1 THz, depending on doping and temperature; the two length scales $\lambda_c = \gamma\lambda_{ab}$ and $\lambda_{ab} \approx 200/(1 - T^2/T_c^2)^{1/2}$ nm, with $T_c \approx 90$ K and $\gamma \approx 300$–600, determine the characteristic scales of magnetic field variations parallel (along the x-axis, i.e., along the layers and perpendicular to JVs) and perpendicular (along the y-axis, $y \| c$) to the superconducting layers. The set (1) of equations can be derived from the standard coupled Sine-Gordon equations for the gauge invariant phase differences ϕ_{n} in Josephson junctions with the assumption that the nonlinearity is essential only for the "central" junction where a JV moves. This assumption has been proven both analytically and numerically. The equation for the gauge invariant phase difference ϕ in the central junction has its own space and time scales: l and $\omega_{\mathrm{J}^*}^{-1}$. There K_0 denotes the modified Bessel function usually used for the magnetic field distribution in superconductors. When all Josephson junctions are the same (e.g., as in standard $Bi_2Sr_2CaCu_2O_{8+\delta}$ samples), $\omega_{\mathrm{J}^*} = \omega_{\mathrm{J}}$, and the size $l = \gamma s$ where s is the spacing between CuO_2 planes. For a weaker internal Josephson junction, the Josephson soliton is more elongated, $l = l_{\mathrm{w}} = \gamma s J_c/J_c^{\mathrm{w}}$, and $\omega_{\mathrm{J}^*} = \omega_{\mathrm{w}}$ is determined by the parameters of the weaker junction: $\omega_{\mathrm{w}} = \omega_{\mathrm{J}}(s_{\mathrm{w}} J_c^{\mathrm{w}} \varepsilon / s J_c \varepsilon_{\mathrm{w}})^{1/2}$ where J_c and ε are the maximum allowed superconducting current and the dielectric constant of the intrinsic junctions; the index "w" refers to the internal weaker Josephson junction.

4. Generating continuous radiation

Eq. (1) for the magnetic field H allows us to obtain the spectrum of EM waves propagating in the layered structure

$$\begin{aligned} &\omega^2 = \omega_{\mathrm{J}}^2 + c_{\mathrm{J}}^2 k_x^2, \\ &c_{\mathrm{J}}(k_y) = \omega_{\mathrm{J}} \lambda_c / (1 + \lambda_{ab}^2 k_y^2)^{1/2}. \end{aligned} \tag{2}$$

The minimum vortex velocity $c_{\min}$ needed for Cherenkov radiation ($c_{\min} \approx c_{\mathrm{J}}(k_y = \pi/s) \approx \gamma s \omega_{\mathrm{J}}/\pi$), and the characteristic angle

$$\theta = \mathrm{atan}\{\pi(V^2 - c_{\min}^2)^{1/2}/\omega_{\mathrm{J}} s\} \tag{3}$$

of the propagating JPW are determined by three conditions: (i) Eq. (2), (ii) $\omega = k_x V$, and (iii) the minimum wavelength $k_y \approx \pi/s$.

However, the JVs cannot move above the maximum speed $V_{\max}$ determined by the nonlocal Eq. (1): $V_{\max} \approx \omega_{\mathrm{w}} l_{\mathrm{w}}$ for samples with some weaker junctions. Using Eq. (1) we calculate perturbatively the intensity of the Cherenkov radiation

$$H_{\text{Cherenkov}} = (\Phi_0/2\pi\lambda_{ab}^2) \times \int (\mathrm{d}k_x/k_y)\exp(-k_x l) \times \sin[k_x(x - Vt) + k_y \mid y \mid], \tag{4}$$

where integration is performed for $k_x > k^* = \omega_{\mathrm{J}}/(V^2 - c_{\min}^2)^{1/2}$ and for $k_y = \omega_{\mathrm{J}}(1 + \lambda_c^2 k_x^2)^{1/2}/[\lambda_{ab}(k_x^2 V^2 - \omega_{\mathrm{J}}^2)^{1/2}]$. The distribution of the magnetic field for this Cherenkov radiation is shown in Fig. 1. Due to the rather unusual dispersion relation (2), i.e., the decay of $k_y(k_x, \omega = k_x V)$ with increasing k_x, and the nonlocal properties of JVs the electromagnetic waves are located outside the Cherenkov cone (Fig. 1(a), which is drastically different from the Cherenkov radiation of a fast relativistic particle. The new type of radiation predicted here could be called outside-the-cone Cherenkov radiation.

4.1. Creating vortex–antivortex pairs

Another interesting relativistic effect can occur when a Josephson vortex in a very weak junction moves much faster than the maximum velocity of Josephson vortices in the nearby intrinsic junctions [12]. In this case, the fast modulation of the phase difference, created by this fast vortex in a weaker junction, cannot relax in the neighboring junctions producing a chain of von Karman-like vortices and antivortices which gradually annihilate. Note that the gauge phase oscillations behind the fast Josephson vortex, reported in [13,14], could be also interpreted as precursors of vortex–antivortex pairs.

5. Generating THz pulses

Modern sample-preparation techniques also allow the modulation of superconducting properties (e.g., resistivity along the *ab*-plane) in the weaker junctions. For a fixed total *c*-axis current, this resistivity modulation results in an *ab*-in-plane modulated voltage drop across the weaker junctions and, thus, modulating the electric field $E_y(x)$ in the weaker junctions. Since the JV speed V is proportional to the electric field $E_y(x)$ in the junction, then V periodically changes along the junction. Therefore, V can be adjusted so as to be faster than the minimum velocity $c_{\min}$ of the EM wave in some parts of the junction with large resistivity, but smaller than $c_{\min}$ in other parts, with low resistivity. In this case, the JVs produce flashes of outside-the-cone Cherenkov radiation [12] when passing these interfaces. Varying the in-plane magnetic field H_{ab} changes the distance $a_{\mathrm{J}} = \Phi_0/(D_{\mathrm{w}} H_{ab})$ between JVs, where D_{w} is the distance (along the *c*-axis) between the weaker junctions. When a_{J} is larger than the period of the resistivity modula-

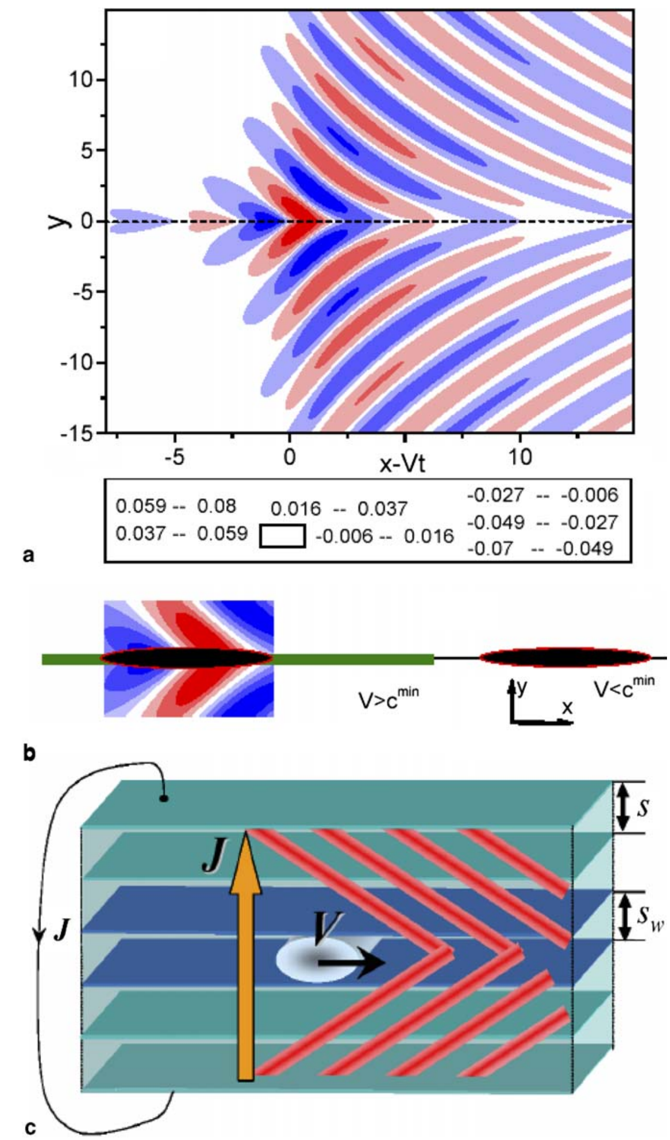

Fig. 1. Cherenkov radiation generated by a fast Josephson vortex (located at $x = Vt$) moving in a weaker junction. (a) Magnetic field distribution $H(x - Vt, y)$ in units of $\Phi_0(2\pi\lambda_c\lambda_{ab})$ for $J_c^w/J_c = 0.2, s_w\varepsilon/(s\varepsilon_w) = 1.2, V/V_{\max}^w = 0.9$. The "running" coordinate, x-Vt, is measured in units of $\gamma s/\pi(v^2\beta^2 - 1)^{1/2}$ with $v = V/c_{\min}$, while the out-of-plane coordinate y is normalized by $s/(\pi(v^2\beta^2 - 1)^{1/2}$, where $\beta = \pi J_c \varepsilon s_w / 2J_c^w \varepsilon^w s$. The moving vortex emits radiation propagating forward. This radiation forms a cone determined by the vortex velocity V. (b) Varying both, the out-of-plane and in-plane properties of a sample (for instance, via sample irradiation) one could achieve pulsating THz radiation if the Josephson vortices move faster than $c_{\min}$ in some parts of a sample (unirradiated green segments in (b)) and slower in other parts. (c) A suggested experimental set up: in a weaker junction an out-of-plane current $J \| c$ drives a Josephson vortex with velocity V, which is higher than the minimum velocity $c_{\min}$ of the propagating electromagnetic waves. A sample having one or several weaker Josephson junctions (located between the two blue superconducting planes in (c)) could be prepared by varying chemical components in Bi2212/Bi2201/Bi2223 or by a more controllable sample preparation using, e.g., CVD. Red strips in (c) schematically show outside-the-cone Cherenkov radiation.

tions, the artificial stack with weaker junctions emits Cherenkov radiation with a certain delay between pulses, thus, working as a pulsed THz generator [12]. Increasing H_{ab}

decreases the distance between Josephson vortices, finally squeezing two or more vortices per period of the spatial modulation of the resistivity. This dense JV lattice generates continuous THz radiation. Therefore, the inter-pulse delay time of the THz pulse emitter can be tuned by the in-plane magnetic field H_{ab} up to reaching the continuous-radiation regime.

6. Conclusions

Recently, we propose [5,7,10,12] a set of experimentally realizable devices to control THz radiation using layered strongly anisotropic superconductors. The proposed THz tools include:

(1) THz emitters;
(2) THz filters;
(3) THz detectors.

For the case of emitters, we propose [10] to use modulated Bi2212 samples to generate THz radiation. The new type of radiation (the out-of-plane radiation) can be generated in this case. In contrast to all previous proposals, this type of radiation has a strong electric field and can easily pass the superconductor–vacuum interface (so we propose a way to overcome impedance mismatch, which is very strong for the devices proposed in [2]).

For THz filters, we propose [5] to use Bi2212 and control the transmissivity and reflectivity by changing the in-plane magnetic field. For this case, we predict the tunable photonic gap structure (tunable photonic crystal). In principle a somewhat similar effect could be found for the out-of-plane field.

Our suggested design for THz detectors [7] is based on the novel surface Josephson plasma wave, which can propagate along the superconductor–vacuum surface when the wave frequency is below the Josephson plasma frequency. We derive that the incident THz wave can resonantly excite the surface wave at certain angles between the incident wave and the sample surface. This results in a strong increase of absorption of THz wave in the sample and resonant peak of the sample resistance at these angles. The position of the peak and their relative heights allows to estimate the frequency direction and intensity of the incident THz wave.

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