Using Josephson Vortex Lattices to Control THz Radiation: How to generate, filter, and detect radiation using layered superconductors

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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, 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 controllable photonic band gap structure (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. 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.

Spatially modulated samples as emitters of out-of-plane radiation and impedance mismatch problem

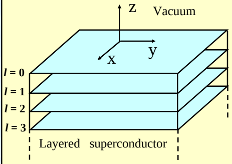
Model of layered superconductors

$$\left(1-\frac{\lambda_{ab}^2}{D^2}\Delta_l\right)\left(\frac{\partial^2\varphi_l}{\partial t^2}+\omega_J^2(1+\underbrace{\mu(x)}_{\text{Spatial modulations}})\sin(\varphi_l)\right)-\frac{c^2}{\varepsilon}\frac{\partial^2\varphi_l}{\partial x^2}=0$$

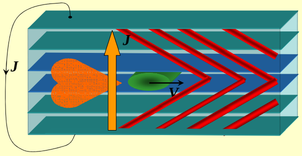
$$\Delta_l f_l = f_{l+1}+f_{l-1}-2f_l$$

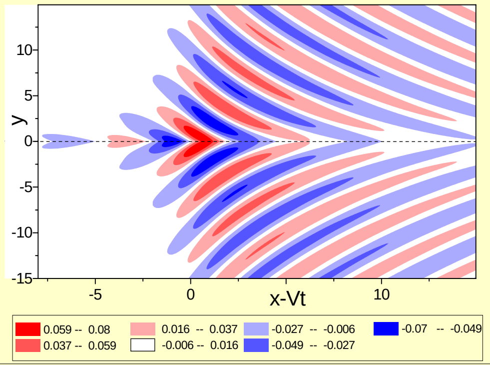
Josephson plasma frequency = $\omega_J/2\pi \sim 1\,\mathrm{THz}$

Gauge invariant phase difference of the order parameter = φ_l



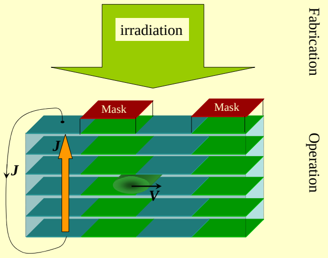
A suggested experimental set up: in a weaker junction an out-of-plane current $J||c$ drives a Josephson vortex with velocity V, which is higher than the minimum velocity c_{min} of the propagating electromagnetic waves. Red strips in schematically show outside-the-cone Cherenkov radiation.





Cherenkov radiation generated by a fast Josephson vortex (located at $x=Vt$) moving in a weaker junction. 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.

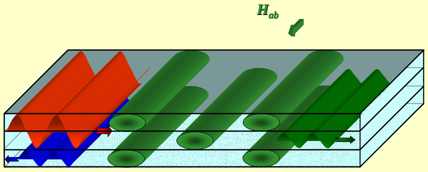
Sample



A sample having one or several weaker Josephson junctions (located between the two blue superconducting planes in (b)) could be prepared by varying chemical components in Bi2212/Bi2201/Bi2223 or by a more controllable sample preparation using, e.g., CVD.

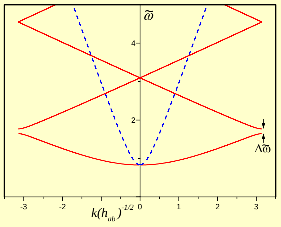
THz filters controlled by in-plane magnetic field: tunable photonic crystal

Tunable THz Filter

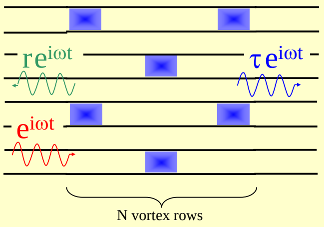


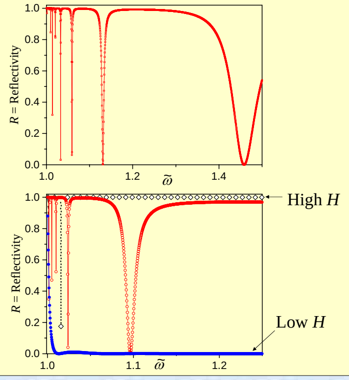
The array of green cylinders inside the sample, forming a so-called photonic crystal, span the width of the sample. These cylinders contain a magnetic field, and act somewhat similarly to bumpers in a pinball machine, scattering the incident electromagnetic waves, shown in red. Only red waves with certain frequencies can propagate through the crystal, resulting in the outgoing transmitted wave shown in green. The rest bounce back, shown as the reflected blue waves.

Tunable photonic bang gap structure

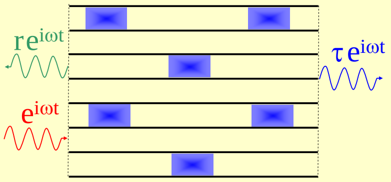


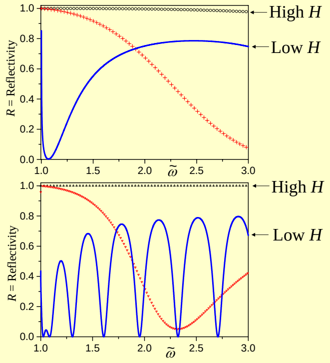
Internal Reflection





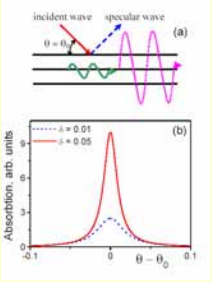
Reflection of the incident wave





Using surface Josephson plasma waves for THz detectors

Resonant excitation of surface waves



Model for breaking charge neutrality

$$\left(1-\frac{\lambda_{ab}^2}{D^2}\partial_l^2\right)\left(\frac{\partial^2 H^l}{\partial t^2}+\underbrace{\omega_r\frac{\partial H^l}{\partial t}}_{\text{damping}}+\omega_J^2H^l-\underbrace{\alpha\omega_J^2\partial_l^2}_{\text{charge neutrality breaking}}H^l\right)-\frac{c^2}{\varepsilon}\frac{\partial^2 H^l}{\partial x^2}=0.$$

References:
[1] S. Savel'ev, A.L. Rakhmanov, F. Nori, Phys. Rev.Lett. **94**, 157004 (2005).
[2] S. Savel'ev, V. Yampol'skii, A. Rakhmanov, F. Nori, Phys. Rev. B **72**, 144515 (2006).
[3] S. Savel'ev, V. Yampol'skii, F. Nori, Phys. Rev. Lett **95**, 187002.