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Emission of terahertz electromagnetic waves by vortex flow in high-T_c superconductors

Masashi Tachiki [a,*], Mikio Iizuka [b], Kazuo Minami [b], Shogo Tejima [b], Hisashi Nakamura [b]

[a] *National Institute for Materials Science, 1-2-1 Sengen, Tsukuba 305-0047, Japan*
[b] *Research Organization for Information Science and Technology, 2-2-54 Nakameguro, Meguro-ku, Tokyo 153-0061, Japan*

Abstract

Continuous terahertz electromagnetic waves have new applications in scientific and industrial fields such as medicine and information technology. Cuprate high-temperature superconductors have a layer structure, and form a naturally multi-connected Josephson junction system called intrinsic Josephson junction (IJJ). In IJJ, there appears a new excitation called the Josephson plasma. Its frequency is in the region of terahertz inside the superconducting energy gap. The excited plasma wave is converted into an electromagnetic wave at sample surfaces. Therefore the IJJ has a great potential to generate terahertz continuous wave. Here we report the results of simulations to find the optimum condition for obtaining the strongest emission power of the terahertz waves. The simulations were carried out using our theory. Since the simulation uses very large-sized coupled nonlinear equations therefore difficult to compute, we used the fastest supercomputer named as Earth Simulator. We found that the quite intense continuous terahertz coherent wave is emitted from a small sample with high-energy efficiency.

Keywords: Vortex flow; Terahertz electromagnetic emission

1. Introduction

Terahertz electromagnetic waves can be applied to many field; medical diagnoses, materials inspection, broadband communication technology etc. One of the main hurdles in developing terahertz wave technology is the development of sources for intense continuous terahertz waves.

Fig. 1 shows a prototype unit of a terahertz emission device using, in this case, $Bi_2Sr_2CaCu_2O_{8-\delta}$. In this Fig. 1 the green part shows an IJJ sandwiched by electrodes made of the same metal. In the junction, current flows uniformly in the direction indicated by the arrow for J. An external magnetic field applied in the direction of the y-axis induces fluxons. Fluxons driven by an external current attain a speed several percent of the light velocity in good single crystals. The fast motion of these fluxons induces a flow voltage along the z-axis, and this voltage brings about an oscillating superconducting current through the AC Josephson effect. This oscillating current excites the Josephson plasma, which gives rise to terahertz electromagnetic waves.

In accord with the above mechanism, we derive the equations for simulating the terahertz wave generation. The superconducting order parameter of the ℓth layer is expressed as $\psi_\ell(\boldsymbol{r}) = \Delta_\ell e^{i\varphi_l(\boldsymbol{r})}$. In the system, current along the z-axis perpendicular to the CuO_2 plane is expressed as

$$j_{z,\ell+1,\ell}(\boldsymbol{r}) = j_c \sin \psi_{l+1,\ell}(\boldsymbol{r}) + \sigma_c E_{z,\ell+1,\ell}(\boldsymbol{r}) + (\varepsilon_c/4\pi)\partial_t E_{z,\ell+1,\ell}(\boldsymbol{r}) \quad (1)$$

where j_c is the critical current and $\psi_{\ell+1,\ell}(\boldsymbol{r})$ is the gauge invariant phase defined by

$$\psi_{\ell+1,\ell}(\boldsymbol{r}) = \varphi_{\ell+1}(\boldsymbol{r}) - \varphi_\ell(\boldsymbol{r}) - \frac{2\pi}{\phi_0}\int_{z_\ell}^{z_{\ell+1}} dz A_z(\boldsymbol{r}, z) \quad (2)$$

* Corresponding author.
E-mail address: tachiki.masashi@nims.go.jp (M. Tachiki).

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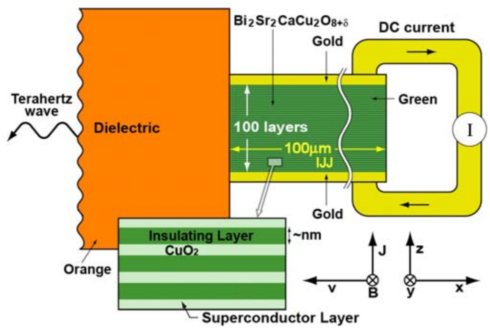

Fig. 1. Schematic diagram of a prototype model for terahertz emission.

with the vector potential $A_z(\boldsymbol{r}, z)$ and the flux unit Φ_0. For superconducting current densities in the CuO_2 plane, we use the generalized London equations, since the Landau parameter is very large in cuprate superconductors:

$$j_\ell^\alpha(\boldsymbol{r}) = -\frac{c}{4\pi\lambda_{ab}^2}\left(A_\alpha(\boldsymbol{r}, z_\ell) - \frac{\phi_0}{2\pi}\partial_\alpha(\varphi_\ell(\boldsymbol{r}))\right) \tag{3}$$

with $\alpha = x$ and y, and the penetration depth λ_{ab}. Since the superconducting CuO_2 layers are so thin, λ_{ab} is better to be consider a parameter for the superconducting layer. The charge density of the ℓth layer is given by

$$\rho_\ell(\boldsymbol{r}) = -\frac{1}{4\pi\mu^2}\left(A_0(\boldsymbol{r}, z_\ell) + \frac{\phi_0}{2\pi c}\partial_t\varphi_\ell(\boldsymbol{r})\right) \tag{4}$$

with the Debye screening length μ and the scalar potential $A_0(\boldsymbol{r}, z)$. We insert the current and charge expressions (1)–(4) into Maxwell's equations, and after cumbersome calculations [1] we have

$$\begin{aligned}&\left(1 - \zeta\Delta^{(2)} + s'd'\zeta\eta\partial_{t'}\right)\left(\partial_{t'}^2\psi_{\ell+1,\ell} + \beta\partial_{t'}\psi_{\ell+1,\ell} + \sin\psi_{\ell+1,\ell}\right)\\ &\quad + \alpha s'\left[\partial t'(\rho'_{\ell+1} - \rho'_\ell) + \beta(\rho'_{\ell+1} - \rho'_\ell)\right]\\ &\quad = \left(\partial_{x'}^2 + \partial_{y'}^2\right)(1 + s'd'\zeta\eta\partial_{t'})\psi_{\ell+1,\ell}\end{aligned} \tag{5}$$

$$s'(1 - \alpha\Delta^{(2)})\rho'_\ell = \partial t'(\psi_{\ell+1,\ell} - \psi_{\ell,\ell+1}) \tag{6}$$

for the IJJ. In the above equation, we used reduced units for length, time, and electronic charge etc., defined as

$$x' = x/\lambda_c, \quad t' = \omega_p t, \quad \rho' = \lambda_c\omega_p\rho/j_c, \quad \text{and} \quad \omega_p = c/(\sqrt{\varepsilon_c}\lambda_c) \tag{7}$$

ω_p being the Josephson plasma gap frequency and ε_c the dielectric constant along the z-axis. The parameters in Eqs. (5) and (6) are defined as

$$\begin{aligned}&\zeta = \lambda_{ab}^2/(sd), \quad \alpha = \varepsilon_c\mu^2/(sd), \quad s' = s/\lambda_c, \quad d' = d/\lambda_c\\ &\beta = 4\pi\sigma_c\lambda_c/(\sqrt{\varepsilon_c}c), \quad \text{and} \quad \eta = 4\pi\sigma_{ab}/(\varepsilon_c\omega_p)\end{aligned} \tag{8}$$

ρ_ℓ is the charge density in the ℓth CuO_2 layer, σ_c in β is the quasi-particle conductivity along the c-axis in the superconducting state, s and d in ζ and α the thickness of the superconducting and insulating layers, respectively. ζ and α are the inductive and capacitive interaction constants. The operator is defined as $\Delta^{(2)}f_\ell = f_{\ell+1} - 2f_\ell + f_{\ell-1}$.

2. Emission from the *bc* surface [2]

In Fig. 1 the orange part shows the dielectric material, which guides terahertz electromagnetic waves from the device to the outer area. Maxwell's equations are applied to the waves in the dielectric. We use the finite difference method to perform the numerical simulation. We made the interface connection between the IJJ and the dielectric in the following way: we determine the z component of the electric field in one cell of the finite difference mesh between the IJJ and the dielectric by applying Ampere's law and the magnetic field by applying Faraday's law at both the boundaries of the cell. We chose $\lambda_c = 150$ μm, $\beta = 0.01$–0.05, $s = 3$, $d = 12$, $\mu = 6$, $\alpha = 0.1$, applied a magnetic field of 2 T, and took the dielectric constants along the z-axis in the IJJ and that of the wave guide to be $\varepsilon = 10$. The λ_{ab} was taken to be 0.18 μm. We changed the external current J/J_c, J_c being the critical field current at zero magnetic fields, from 0.0 to 1.5 in steps of 0.1 and obtained the emission power by calculating the Poynting vector at a location 2 μm from the surface of the IJJ in the dielectric. For each external current, the time evolution was simulated until the system reached a stationary state after the reduced time $t' = 600$, and the emission power was calculated after that time. The length of the IJJ is taken to be 50 μm along the x-axis and the number of layers along the z-axis is taken to be 300. The length of the dielectric along the a-axis is 100 μm. The boundary conditions on the left surface of the IJJ are assumed to be perfect reflection. The superconducting current along the z-axis in the top and bottom electrodes is assumed to penetrate to 0.075 μm. The electromagnetic wave is assumed not to be reflective at the end surface of the dielectric.

When we apply an external current along the z-axis of the IJJ in an external magnetic field parallel to the y-axis, motion of fluxons induces a flow voltage along z-axis. This lvoltage creates oscillating current due to the AC Josephson effect and the current induces electric and magnetic fields along the z and y axes, respectively. $J/J_c = 0.4$ is 1.67 THz. The wavelength of the excited electromagnetic field is approximately twice the average distance between the fluxons.

The emission power (the Poynting vector) measured at a location 2 μm from the interface between the IJJ and the dielectric in Fig. 1, assuming that the length of depth is 10 μm along y-axis. The emission power has peaks at external currents $J/J_c = 0.4$ and 0.7 with the powers 0.91 mW and 0.40 mW, respectively. The first peak occurs when the wavelength is approximately equal to twice the average distance between the fluxons, and the second peak occurs when the wavelength is equal to the average distance between the fluxons. The frequency is analysed by FFT