THz Wave Emission from the Intrinsic Josephson Junctions of High $T_c$ Superconductors

H. Matsumoto$^{1,3}$, T. Koyama$^{1,3}$, M. Machida$^{2,3}$ and K. Kadowaki$^4$

$^1$Institute for Materials Research, Tohoku University, Sendai 980-8577, Japan
$^2$CCSE, Japan Atomic Energy Agency, 6-9-3 Higashi-Ueno, Taito-ku, Tokyo 110-0015, Japan
$^3$CREST(JST), 4-1-8 Honcho, Kawaguchi, Saitama 332-0012, Japan
$^4$Institute of Materials Science, University of Tsukuba, Tsukuba, Ibaraki 305-8577 Japan

E-mail: matumoto@ldp.phys.tohoku.ac.jp, tkoyama@imr.tohoku.ac.jp, machida.masahiko@jaea.go.jp, kadowaki@ims.tsukuba.ac.jp

Abstract. Relating to the recent observation of a THz wave emission from the intrinsic Josephson junction of Bi-2212, we investigate temporal and spatial behaviors of electromagnetic fields around the junctions by numerical simulation. We consider 1) xz-model, where junctions and leads are stacked in the $z$-direction with homogeneity in the $y$-direction, and 2) xy-model, where junctions have a rectangular shape in the xy-plane with homogeneity in the $z$-direction. The result of the xz-model shows that the emitted electromagnetic field has the spatial pattern similar to that of the dipole emission. The result of the xy-model shows that waves are emitted in the all directions of the xy-plane and the frequency of the oscillation is controlled by the shorter length and is given by the Josephson frequency. The voltage-dependence and the angle-dependence of the emitted power are also studied.

1. Introduction

Recently, Ozyuzer et al.[1] succeeded in observing directly a strong emission of terahertz electromagnetic waves by using mesa-shaped samples of the high $T_c$ superconductor Bi$_2$Sr$_2$CaCu$_2$O$_8$ (BSCCO) intrinsic Josephson junctions (IJJs) without any applied magnetic field. The size of the junction is about 300$\mu$m $\times$ (40-100)$\mu$m, which is nearly the c-axis magnetic penetration depth $\lambda_c$. The largest voltage branch was chosen, and in the bias current decreasing process below the critical current, a strong wave emission is observed near the unstable point of the retrapping current. The emitted electromagnetic waves are highly monochromatic.

Theoretical studies of the terahertz wave emission from IJJs has been discussed by various authors[2, 3, 4, 5, 6] mostly with an applied magnetic field. The case without an applied field was discussed recently in ref. [7] with the result that a shorter system size of a few $\mu$m is preferable, which does not agree with the experiment. In the previous papers[8, 9], we analyzed the voltage dependence of the emitted power, by assuming the in-phase motion of the superconducting phase-differences. The emitted power gradually increases with the decreasing voltage, taking the maximum power at the retrapping current. Experimentally, strong emissions occur sharply in quite restricted voltage region. It was pointed out that effects of out-of-phase motions through the interlayer couplings makes the resonating nature much sharper[9].

Recently, in refs.[10] and [11], it was pointed out that a careful choice of boundary conditions leads to a solution for vortex-lines to penetrate in an alternative direction layer by layer,
having a sharper resonating nature. In this case, the electric field inside the junction takes an antisymmetric spatial distribution, while in refs.[8, 9] the oscillating electric field has a spatially constant part plus a symmetric spatial distribution. The former pattern is obtained in the antenna theory of an open cavity[12, 13], while the latter pattern is obtained in the wave emission from the capacitor applied with an oscillating bias current[14]. Two cases give different spatial distribution of the emitted power; the former has the maximum power in the direction orthogonal to the junction-plane, while the latter has the maximum power in the direction parallel to the junction-plane.

In this paper we investigate the spatial distribution and oscillatory pattern of electromagnetic fields inside and outside of the junction, by taking into account the two-dimensional size effect. The result shows the same wave patterns as those emitted from the capacitor with an oscillatory bias current.

2. Formulation

![Illustrations of models: (a) the xy-model, a junction (L_x × L_y) at the center plus the surrounding vacuum with the PML outside, (b) the xz-model, a lead-junction-lead at the center plus the surrounding vacuum with the PML outside. \( j_{\text{ext}} \) is a bias current.](image)

Figure 1. Illustrations of models: (a) the xy-model, a junction (\( L_x × L_y \)) at the center plus the surrounding vacuum with the PML outside, (b) the xz-model, a lead-junction-lead at the center plus the surrounding vacuum with the PML outside. \( j_{\text{ext}} \) is a bias current.

We consider two cases as illustrated in Fig. 1 (a) and (b); (a) the xy-model where the junction has two-dimensional size of \( L_x × L_y \) and the homogeneity along the z-axis is assumed, and (b) the xz-model where the system of leads and junctions have a finite thickness and the homogeneity along the y-axis is assumed. The bias current \( j_{\text{ext}} \) is injected into the leads. The system and the vacuum are surrounded by the Berenger’s perfectly matched layers (PML)[15] which absorbs propagating waves without reflection. We consider in-phase motions in the intrinsic Josephson junctions, so that the system is essentially same as a single junction.

Equations among the phase-difference \( \phi \) and electromagnetic fields in the junctions are given by \( B_z = 0, E_x = E_y = 0 \) and \( (1/\omega_p)\partial_t \phi = E_z/E_p, B_x/B_c = -\lambda_c \nabla_y \phi, B_y/B_c = \lambda_c \nabla_x \phi \) and \( (1/\omega_p)\partial_t (E_z/E_p) = \lambda_c (\nabla_x B_y/B_c - \nabla_y (B_x/B_c)) - \sin \phi - \beta (E_z/E_p) \), where \( \omega_p \) is the angular Josephson frequency, \( \lambda_c \) is the penetration depth along the c-axis, given by \( c/\sqrt{\epsilon \omega_p} \) with \( \epsilon \) being the dielectric constant of the insulating layers and \( \beta \) is a dissipation constant. The scale of the electric and inductive fields are given, respectively, as \( E_p = \hbar \omega_p/2 e d \) and \( B_c = \hbar c/2 e d \lambda_c \) with \( d \) being the thickness of the insulating layers. The Maxwell equations inside the leads and the vacuum are given as \( (1/\omega_p)\partial_t (\epsilon_0/\epsilon)(\vec{E}/E_p) = \lambda_c \vec{\nabla} \times (\vec{B}/B_c) - (\vec{j}/j_c), (1/\omega_p)\partial_t (\vec{B}/B_c) = -\lambda_c \vec{\nabla} \times (\vec{E}/E_p) \).

2.1. xy-model

The relevant field are \( \phi(x, y, t), E_z(x, y, t), B_x(x, y, t) \) and \( B_y(x, y, t) \). The condition of the bias current is given from the Ampere’s law as \( \int_C \vec{dl} \cdot \vec{B}_{\text{DC}} = (4\pi/c)j_{\text{ext}} L_x L_y \), where the contour \( C \) is taken anticlockwise along the edge of the junctions and the subscript ‘DC’ indicates the DC-component.
2.2. xx-model

The relevant field are \( \phi(x,t) \), \( E_x(x, z, t) \), \( E_y(x, z, t) \) and \( B_y(x, z, t) \). The bias current \( j_{ext} \) is injected at the position of \( \pm L_{ij} \) in the leads. One may regard its effect as a transparent wire. Then in the Maxwell equation, we have \( j_{x,y}/j_c = 0 \) in the vacuum \( \beta_L E_{x,y}/E_p \) in the leads, \( j_z/j_c = (j_{ext}/j_c) \theta(L_{ij} + z) \theta(L_{ij} - z) \theta(x + L_x/2) \theta(L_x/2 - x) + \beta_L E_z/E_p \) in the leads.

The emitted power in a \( \vec{n} \)-direction at a position \( \vec{r} \) is obtained by taking the time average of the Poynting vector evaluated from oscillatory parts of electromagnetic fields, \( S_p(\vec{r}) = (c/4\pi(t_{max} - t_{min})) \int_{t_{min}}^{t_{max}} dt \vec{n} \cdot ((\vec{E}(\vec{r}, t) - \vec{E}_{stat}(\vec{r})) \times (\vec{B}(\vec{r}, t) - \vec{B}_{stat}(\vec{r}))) \).

3. Results

In the present analysis we choose the parameters as \( \beta = 0.05 \), \( \epsilon = 10.0 \). The emitted power is scaled by \( S_p = \frac{c}{2\pi} E_p B_c \). In Fig.2, the calculated results of the xy-model are summarized. Fig. 2(a) shows a typical spatial wave pattern of the induction field \( \vec{b} = (\vec{B}(x, y, t) - \vec{B}_{stat}(x, y)) \),

where the subscript "stat" indicates the static part. The height is for the magnitude of \( \vec{b} \) and the vector indicates its direction. The wave propagates in all the direction, and inside the junction one can see the vortex-antivortex lines in the \( y \)-direction. The local structures of the wave compensate. The calculation shows that the frequency of the expanding wave is given by the Josephson frequency. Fig. 2 (b) is for the angular dependence of the emitted power at \( V/V_p = 3.25 \) with \( V \) being a voltage per junction and \( V_p = E_p d \). \( L_{obs} \) is the distance of the center. The emission in the \( y \)-direction, that is from the longer side, is stronger. Fig. 2(c) is the voltage-dependence of the emitted power for several directions, which is indicated by \( \vec{n} = (n_x, n_y, n_z) \). The dashed line is for one-dimensional model with \( L_x/\lambda_c = 1.0 \). We can see that the resonating nature becomes much sharper.

In Fig.3, the results of the xz-model are summarized. Fig. 3(a) shows a typical spatial wave pattern of the electric field \( \vec{e} = (\vec{E}(x, z, t) - \vec{E}_{stat}(x, z)) \). The height is for the magnitude of \( \vec{e} \). The pattern is similar to the one seen in the dipole emission. Fig. 3 (b) is for the angular dependence of the emitted power at \( V/V_p = 3.15 \). \( L_{sub} \) is the length of the substrate, i.e. the length of the lower lead. With a longer substrate (dotted lines), effects of the reflection is seen. Fig. 3(c) is the voltage-dependence of the emitted power for several directions. We can see that the resonating nature becomes sharper.

Sharp drops occur at lower voltage-sides of peaks in Fig. 2(c) and at higher voltage-side of peaks in Fig. 3(c). We expect that the resonating nature may become much sharper in the three dimensional case, having both properties.
4. Summary

In this paper we investigated the spatial distribution and oscillatory pattern of electromagnetic fields inside and outside of the junction. In the xz-model, we have the emitted wave which has the spatial pattern similar to that in the dipole emission, so that the strongest emission is in the x-direction as in the emission from a capacitor with an oscillating bias current. The Josephson current may play a role of an oscillatory bias current to a capacitor. In the xy-model, the wave is emitted all the direction of the xy-plane, strongest in the longer junction side. The vortex-antivortex lines penetrate parallel to the shorter side of the rectangular, forming a flux line loop, and the oscillation frequency is controlled by the oscillation of those vortex lines, which is same as the Josephson frequency.

Acknowledgments

One of the authors (H. M.) thanks Prof. N. Toyota for useful discussions. This work was supported partially by Grant-in-Aid for Scientific Research on Priority Area, and JSPS Core-to-Core Program Strategic Research Networks NES.

References

[1] Ozyuzer L, Koshelev A E, Kurter C, Gopalsami N, Li O A, Tachiki M, Kadowaki K, Yamamoto T, Tachiki T, Gray K E, Kwok W K and Welp U 2007 Science 318 1291
[2] Koyama T and Tachiki M 1995 Sol. St. Comm. 96 367
[3] Machida M, Koyama T, Tanaka A and Tachiki M 2000 Physica C 330 85.
[4] Tachiki M, Iizuka M, Tejima S and Nakamura H 2005 Phys. Rev. B71 134515
[5] Matsumoto H 2006 Physica C437-438 199
[6] Lin S, Hu X and Tachiki M 2008 Phys. Rev. B77 14507
[7] Bulaevsky L N, Koshelev A E 2007 Phys. Rev. Lett. 99 057002
[8] Matsumoto H, Koyama T and Machida M 2008 Physica C468 654
[9] Matsumoto H, Koyama T and Machida M 2008 Physica C (to be published)
[10] Lin S and Hu x 2008 Cond-Mat(arXiv:0803.4244v1)
[11] Koshelev A E 2008 Cond-Mat(arXiv:0804.0146v1)
[12] Balanis C A 1996 Antenna Theory: Analysis and Design (John Wiley & Sons Inc.) p.736
[13] Leone M 2003 IEEE Transactions on Electromagnetic Compatibility 45 486
[14] Feynman R P 1970 The Feynman Lectures on Physics—Mainly electromagnetism and matter (Addison-Wiley Pub. Co.) p.23-1
[15] Berenger J -P 1994 J. Comp. Phys. 114 185