Large Scale Simulation of the Nano-Scale High-Temperature-Superconductor Device for the Generating of Continuous Terahertz Waves

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ABSTRACT

Continuous terahertz waves have important applications in scientific and industrial fields such as medicine and information technology. Many methods (the quantum cascade laser and the photomixing method, etc.) are developed as a continuous terahertz wave source. However, there is a fault that intensity of continuous terahertz waves by present source is very low in range of 1-4THz. Therefore, new source of the continuous terahertz waves is necessary. New hopeful method of a generating terahertz waves via excitation of intrinsic Josephson plasma (IJP) in high-temperature-superconductor device was proposed in 1994. R and D of this device is very difficult because of nonlinearity of IJP that occurs in a very broad time (10as to ns) and space(1nm to several hundred μ m). Furthermore, this device requires a nano-scale electrode, wave-guide, wiring etc. Therefore, we need a large-scale simulation to develop the device. We have performed a large-scale simulation and found a optimum condition of generation of continuous terahertz waves, using Earth Simulator. We present a result of large-scale simulation for the optimum condition of generating continuous terahertz waves through the nano-scale high-temperature-superconductor device and future challenges of development of this nano-scale device.

Keywords: intrinsic Josephson junctions,terahertz resonance, high performance computational resource

1 Introduction

The unexpected plasma phenomenon with the low frequency in the crystal of the high temperature superconductors (HTC) , was found by professor Uchida of The University of Tokyo in 1992. HTC is formed in a single high temperature superconductors crystals of CuO_2 and insulator layers which form a stack of many atomic-scale Josephson junctions which is called as intrinsic Josephson junctions (IJJ). IJJ has two kinds of Josephson plasma, one is the longitudinal plasma vertical to layers(c axis direction), another is the transverse plasma along layers (ab plane).

Afterwards, professor Tachiki of Tohoku University systematized the new phenomenon in the theory, and showed that the plasma oscillation wtih terahertz order is theoretically possible [1],[2]. In addition, the electromagnetic wave absorption of the plasma oscillation of IJJ was observed by professor Matsuda of University of Tokyo. After that professor Tachiki predicted that the excited plasma wave is coverted into a terahertz electromagnetic wave at an edge of IJJ. IJJ has a potential for an important industrial infrastructure technology in next generation; the super-high-speed computer, the storage elements, and high-capacity and high-speed optical communication conversion devices in the highly-networked information society. Leading countries scurry to develop this technology now. Japan is now leading still on both sides of the experiment and the theory research.

The development of the device for the terahertz electromagnetic wave generation is a very difficult only by the experiment, because IJJ have a very strong nonlinearity and the complex behavior. The development research on the simulation base is indispensable. However, this simulation should deal with nonlinear and complex systems and require high performance computational resource. This is because a scale of space and time for simulation is $1nm \sim severalhundred\mu m$ and 10^8 steps by 10as. It takes two years to perform this simulation for only one case by a conventional computer. The Earth Simulator is therefore essentially needed for solving this problem through simulations. So to speak, it can be said that only the earth simulator will enable the next generation super-high-speed computer to develop. We have performed many simulations and got some results. Let us to show our simulation results.

2 Model Equation

The physical system which should be solved consists of IJJ and the external medium. In IJJ, a coupling equation of the gauge-invariant phase difference φ_k, charge ρ and electric field E^z, which is derived from Josephson relation and Maxwell equation, is solved. The gauge-invariant phase difference is a phase difference between superconducting layer l+1 and l layer. It is related to Josephson's superconducting electric current. Maxwell equation is solved at the outside of IJJ. Let us show a formulation for analysis model. The equations Eq. (1), Eq. (2) and Eq. (3) describing the dynamics of the phase difference, charge and electric field are given by

$$\left(1-\frac{\lambda_{ab}^2}{sD}\Delta^{(2)}\right)\left[\frac{\partial^2\varphi_k}{\partial t'^2}+\beta\frac{\partial\varphi_k}{\partial t'}+sin(\varphi_k)+\right.$$

$$\left.\frac{\epsilon\mu^2}{sD}\left(\Delta^{(1)}\frac{\partial\rho_k^{'}}{\partial t'}+\beta\Delta^{(1)}\rho_k^{'}c\right)\right]=\frac{\partial^2\varphi_k}{\partial x'^2}, \quad (1)$$

$$\left(1-\frac{\epsilon\mu^2}{sD}\Delta^{(2)}\right)\rho_{k+1/2}^{'}=\frac{\lambda_c}{s}\Delta^{(1)}\frac{\partial\varphi_{k+1/2}}{\partial t'}, \quad (2)$$

$$\left(1-\frac{\epsilon\mu^2}{sD}\Delta^{(2)}\right)E_k^{'z}=\frac{\partial\varphi_k}{\partial t'}, \quad (3)$$

$$\left(1-\frac{\lambda_{ab}^2}{sD}\Delta^{(2)}\right)B_k^{'y}=\frac{\partial\varphi_k}{\partial x'}, \quad (4)$$

$$\left(1-\frac{\lambda_{ab}^2}{sD}\Delta^{(2)}\right)J_{k+1/2}^{'x}=\frac{1}{s'}\Delta^{(1)}\frac{\partial\varphi_{k+1/2}}{\partial x'}. \quad (5)$$

At outside of IJJ, Maxwell equation is as follws,

$$\frac{\partial\boldsymbol{E}^{'}}{\partial t'}=\boldsymbol{\nabla}\times\boldsymbol{B}^{'}-\boldsymbol{J}^{'}, \quad (6)$$

$$\frac{\partial\boldsymbol{B}^{'}}{\partial t'}=-\boldsymbol{\nabla}\times\boldsymbol{E}^{'}. \quad (7)$$

where $\Delta^{(2)}A_k is A_{k+1}-2A_k+A_{k-1}$, k : number of insulator layer between uperconducting layer l and l+1, σ : conductivity of the quasiparticles, ε : dielectric constant of the insulating layers, μ : the Debye lenght,Φ_0 : unit magnetic state, J_c : critical current density, s, D : superconducting and insulating layer thikness, φ_k : gauge-invariant phase difference in insulator layer k, $\rho_{k+1/2}$: charge density in superconducting layer in k+1/2, E_k^z : electric field in z direction at insulator layer k, λ_{ab} : penetration depth in the ab-plane direction, $\lambda_c=\sqrt{\frac{c\Phi_0}{8\pi^2 DJ_c}}$: penetration depth in the c axis direction, $\beta=\frac{4\pi\sigma\lambda_c}{\sqrt{\varepsilon}c}$, $\omega_p=\frac{c}{\sqrt{\varepsilon}\lambda_c}$: Josephson plasma frequency, $t^{'}=\omega_p t$: normalized time, $x^{'}=x/\lambda_c$: normalized coordinate in x direction, $\rho^{'}=\rho/(J_c/\lambda_c\omega_p)$: normalized charge density, $E^{'z}=E^z/(2\pi cD/\Phi_0\omega_p)$: normalized electoric field, $\boldsymbol{E}^{'}=\boldsymbol{E}/(2\pi cD/\Phi_0\omega_p)$: normalized electoric field, $\boldsymbol{B}^{'}=\boldsymbol{B}/(2\Phi_0\omega_p/cD)$: normalized magnetic field.

These equations are solved by Finite Difference Method. Some research [3] has been done based on this model.

3 Computational Feature of IJJ Simulation

IJJ phenomenon is very strong nonlinear and complex. Many researchers try to understand IJJ phenomenon via experiments and analytical methods. But, it is very hard to understand IJJ phenomenon with only experiments and analytical method. IJJ simulation based on the model equation can show a detail of IJJ phenomenon mechanism, can allow researchers to easily change a conditions of numerical experiments to evaluate the effect of many conditions. Therefore, IIJ simulation opens up great possibilities for a development of IJJ technology.

A scale of space and time for simulation is $1nm \sim several hundred \mu m$ and 10^8 steps by 10as. It takes two years to perform this simulation for only one case by a conventional computer. In addition, many times IJJ simulation which are with combination of many different material properties, device shapes, current supply methods and current control etc is needed to design and optimize the Tera Hz resonance superconductors device. Therefore, IJJ simulation requires high performance computational resource.

We assume that the system is uniform along the y-axis and make two-dimensional calculation in the x-z plan. We used the finite difference method to perform the numerical simulation. The simulation uses very large sized nonlinear equations heretofore difficult to compute; for a simulation using 1.6×10^6spatial cells in the x-z two-dimensional model, it would take two years to simulate one case of10^8 time-steps using a personal computer with a 2GHz processor. Therefore, we used the Earth Simulator that has a peak performance of 40 teraflops and we carried out this simulation in 12 H with 20 nodes of ES.

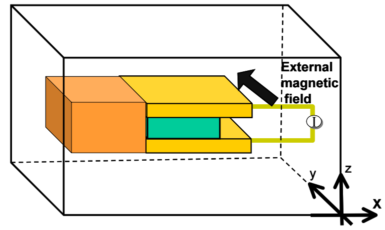

Figure 1: Some small cow spots

4 Simulation Models and Results

Figure 1 shows a prototype unit of a terahertz emission device using, in this case, $Bi_2Sr_2CaCu_2O_{8-d}$.

In this figure the green part shows an IJJ sandwiched by electrodes made of the same crystal. In the junction current flows uniformly in the direction z. An external magnetic field applied in the direction of the y-axis induces fluxons. Fluxons driven by an external current approximately half the critical current attain a speed several hundreds of times smaller than that of light in good single crystals. The fluxons flow in the direction of the x-axis and induce the flow voltage in the direction of the z-axis. The normal current also induces the voltage in the z-axis direction. These voltages creates the oscillating Josephson current along the z-axis by the Josephson effect. This oscillating current excites the Josephson plasma, which gives rise to terahertz electro-

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magnetic waves.

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 impose the following boundary condition. To connect the Josephson plasma wave in the IJJ to the electromagnetic wave in the dielectric at the interface, we put the usual electromagnetic boundary condition; the electric and magnetic fields parallel to the interface are continuous at the interface. The electromagnetic wave in the dielectric is assumed to transmit freely to outer space at the end surface of the dielectric.

We chose $\lambda_c = 100\mu m, \beta = 0.03, 0.1, 0.2, s = 0.3nm, d = 12nm, \mu = 0.6, \alpha = 0.1$, 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 $\lambda_a b$ was taken to be $0.2 \sim 2.0\mu m$. We changed the external current J/Jc from 0.2 to 1.0 in steps of 0.1 and obtained the emission power by calculating the Poynting vector at a location $4\mu m$ 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 $50\mu m$ along the x axis and the number of layers along the z axis is taken to be $10 \sim 1000$. The length of the dielectric along the x-axis is $25\mu m$. 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 $0.075\mu m$. The terahertz wave emitted into the dielectric wave guide at the right hand side is not a perfect plane wave. Therefore, we assume that the small x-axis component of the electric field is not reflective on both the top and bottom surfaces, and the electromagnetic wave is not reflective at the end surface of the dielectric. Making wave guides for terahertz waves is an important future problem.

We searched for the condition which generates a coherent electromagnetic field along the z-axis. We found that, in order to obtain the strongest emission power, 300 layers with $\lambda_a b = 2.0\mu m$ and $beta = 0.03$ are required. When we apply an external current along the x-axis of the IJJ in an external magnetic field, motion of fluxons induces a flow voltage along z-axis. This voltage creates oscillating electric and magnetic fields in the z and y axis respectively through the ac Josephson effect. Fig.2 (A) shows the excited electric field which oscillates around the flow voltage 1.06 V at the reduced current J/Jc = 0.4. Fig. 2(B) shows the excited magnetic field which includes the contribution from fluxons. The frequency analysis from an FFT at the peak point for J/Jc = 0.4 is 1.67 THz. This frequency is approximately the

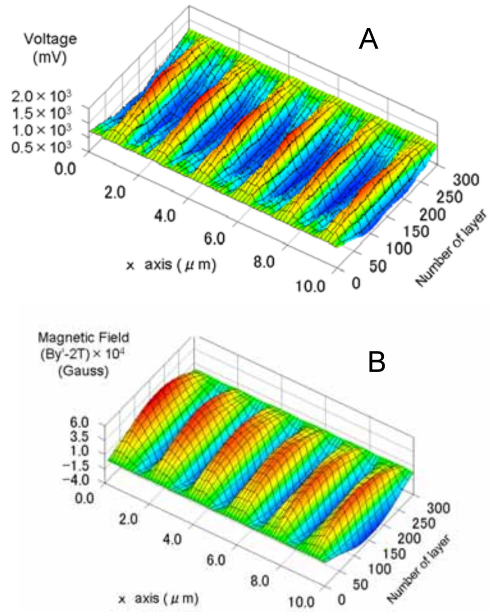

Figure 2: Excited electromagnetic field of a length $10\mu m$at the right surface of the IJJ. (a) Electric field, (b) Magnetic field. Both fields are standing wave like along the x-axis in waveforms. Red and blue indicate the mountain and valley of the field waves, respectively.

same as the frequency 1.77 THz that is estimated from the flow voltage through the simple ac Josephson effect. The wave length of the excited electromagnetic field is twice the average distance between the fluxons.

Figure 3 shows the emission power (the Poynting vector) measured at a location $2\mu m$ from the interface between the IJJ and the dielectric in Fig. 1, assuming that the length is 5mm along y-axis. The emission power has peaks at external currents J/Jc = 0.4 and 0.7 with the powers 90.7mW and 40.2mW respectively. The first peak occurs when the wavelength is 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.

Figure 4 shows the frequency analysed by FFT at the two peaks. These two peaks have frequencies of 1.67 and 2.92 terahertz respectively. The emission powers of these continuous waves are 10^6 times larger than the highest value of the emission power of the continuous waves generated by the conventional laser mixing method [4]. . The frequencies of waves other than 1.67 and 2.92 terahertz also have sharp peaks.

5 Future Work

We have mainly concentrated on finding the condition for generation of continuous coherent terahertz waves up to now.

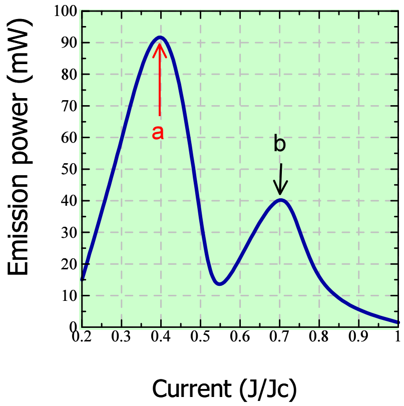

Figure 3: The emission power (mW) at a location $2\mu m$ from the interface in the dielectric. The horizontal scale indicates reduced current. The emission power has peak values at points a and b.

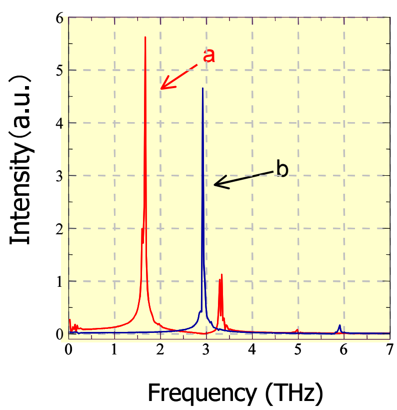

Figure 4: The frequency analysed by FFT at the two peaks a and b in figure.3. The frequencies are those of electromagnetic waves in the dielectric.

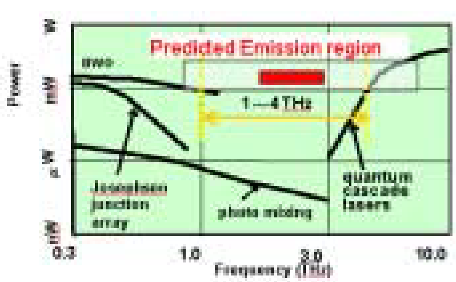

Figure 5: The relation between frequency and power of emission device.

A more wide and general condition for generation of continuous coherent terahertz waves will be studied on Earth Simulator. And 3D code for simulation of device design will be developed.

6 Conclusion

We have found the condition for generation of continuous coherent terahertz waves via large-scale simulation using Earth simulator. That result will lead us developing the new continuous terahertz generating device (Fig.5). We believe that Earth simulator class or over class high performance computational resource only enable us to research and design for terahertz resonance superconductors devices.

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