Josephson Plasma Resonance in Partially-Irradiated $Bi_2Sr_2CaCu_2O_{8+y}$

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Abstract

We study the Josephson plasma resonance (JPR) in $Bi_2Sr_2CaCu_2O_{8+y}$ (BSCCO) with inhomogeneous phase coherence caused by partial introduction of columnar defects. In these BSCCO, we observed several resonances, which can not be regarded as a superposition of those from constituent parts. By calculating linearlized sine-Gordon equation, we can reproduce the above results as well as the existence of a crossover frequency (ω_{cr}) at which the character of JPR changes from irradiated- to pristine-type in partially-irradiated BSCCO.

Key words: $Bi_2Sr_2CaCu_2O_{8+y}$; Joseohson plasma resonance; Columnar defects; partial irradiation

Highly anisotropic high temperature surpercondtors such as $Bi_2Sr_2CaCu_2O_{8+y}$ (BSCCO) can be regarded as stacks of intrinsic Josephson junctions. Recently, Josephson plasma resonance (JPR) has been recognized as a powerful tool to study vortex states [1–5]. This is due to the fact that Josephson plasma frequency (ω_p), which is determined by the gauge-invariant phase difference between neighboring superconducting layers ($\phi_{n,n+1}$), is modified by the presence of vortices as, $\omega_p^2 = \omega_0^2 < \cos\phi_{n,n+1} >$. Here, ω_0 ($= c/\lambda_c\sqrt{\epsilon_0}$) is the Josephson plasma frequency at zero-field (c, λ_c, and ϵ_0 are light velocity, c-axis penetration depth, and dierectric constant.) $< >$ denotes thermal and disorder average [1]. Although many JPR studies have been made on homogeneous systems, little is known about the JPR in systems with inhomogeneous interlayer phase coherence (IPC). To clarify this point, we performed JPR measurements on BSCCO with partially introduced columnar defects which increase the IPC [2]. Our previous results on a heavy-ion-half-irradiated BSCCO crystal (HI-BSCCO) indicated that observed multiple resonances are not a simple superposition of resonances from the constituent parts of the sample with different IPC [6].

In this paper, we report on the detailed JPR measurements in BSCCO with partially introduced columnar defects at various frequencies. We also show the results of numerical simulation of JPR based on the linearized sine-Gordon equation [7].

Single crystals of BSCCO are grown by using the traveling-solvent-floating-zone method. The optimally-doped crystals (T_c= 90.0 K) are irradiated at GANIL by 6 GeV Pb ions at a matching field of B_Φ = 20 kG. A half of the ab-plane is masked by gold foil, which is thick enough to stop all the incident heavy-ions. Typical dimensions of the crystals are $700\times700\times20$ μm^3. JPR is measured by the cavity perturbation method at microwave frequencies of 12.0, 24.2, 41.7, 46.3, 49.4, 52.0, 54.9, 56.6 and 61.2 GHz [5]. The crystal is set in a cylindrical copper cavity so that the microwave electric field is parallel to the c-axis. External magnetic fields up to 90 kOe are applied parallel to the c-axis by a superconducting magnet.

Figure 1 shows microwave power absorption P_{abs}(H) for HI-BSCCO at 50 K for various frequencies. The dashed lines show JPR fields in irradiated and unirradiated samples. The arrow (↓) shows the presence of

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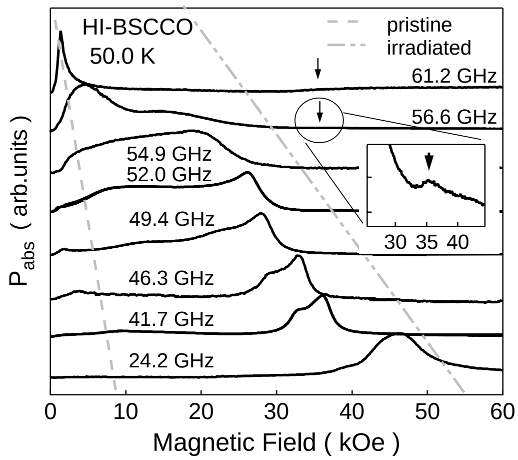

Fig. 1. $P_{abs}(H)$ for HI-BSCCO at 24.2, 41.7, 46.3, 49.4, 52.0, 54.9, 56.6, and 61.2 GHz at 50 K. Arrows indicate the new weak peaks.

a tiny peak (see inset of Fig. 1). Change of frequency does not only shift the resonance field (H_p), but also changes the number of resonance peaks. At 24.2 GHz, only a single resonance peak appears close to the H_p in irradiated sample. As frequency is increased from 24.2 GHz to 61.2 GHz, H_p of the main peak shifts to lower field. Above a crossover frequency of $\omega_{cr} = 55$ GHz, H_p suddenly shifts to lower field. At the same time, new weak peaks (↓) appear.

Next we calculate linearized sine-Gordon equation and compare it with the experimental results. According to Koshelev [7], when the IPC along c-axis is uniform, spatial variation of the amplitude of plasma oscillation ($\theta(x)$) obeys the linearized sine-Gordon equation

$$\left(\frac{\omega^2 + i\nu_c\omega}{\omega_0^2} - C(x)\right)\theta(x) + \lambda_c^2\nabla_x^2\theta(x) = \frac{i\omega D}{4\pi J_0}, \quad (1)$$

where ω and $C(x)$ represents incident microwave frequency and spatial dependence of IPC. ν_c, D, J_0, and λ_c are damping frequency, microwave power, and c-axis penetration length at zero field. In the present case, the spatial distribution of $C(x)$ is

$$C(x) = \begin{cases} C_1 & 0 \le x < L_1 \\ C_2 & L_1 \le x \le L_1 + L_2 \end{cases}. \quad (2)$$

Here, L_1 and L_2 are widths of pristine- and irradiated-part (see Fig.2). Absorption power of microwaves is originated form Joule-heating, so that

$$P(\omega) \propto \frac{\omega^2}{2}\int_0^{L_1+L_2} |\theta(x)|^2 \mathrm{d}x. \quad (3)$$

Figure 2 shows the calculated absorption power as a function of external field. In this calculation, field dependence of the $C(x)$ for each part is quoted from our previous results [6]. We assumed appropriate values of

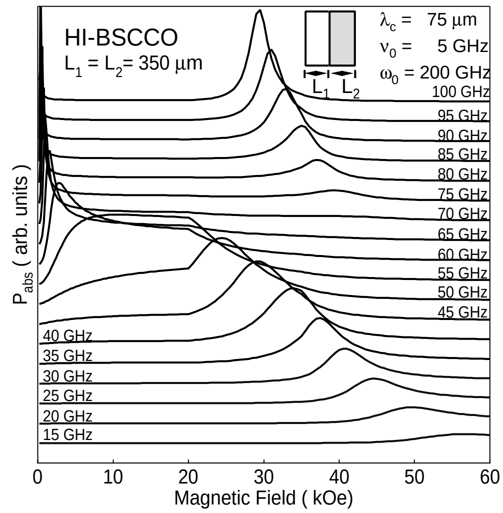

Fig. 2. $P_{abs}(H)$ calculated based on the linearized sine-Gordon equation for position dependent IPC.

ν_c, ω_0, J_0, and λ_c as shown in Fig. 2. A single resonance peak appears near the resonance field for irradiated region below 45 GHz and ω_{cr} exists between 50 GHz to 60 GHz. Above ω_{cr}, new peaks appear at higher field range, which are actually observed in our experiment (see arrows in Fig. 1). The linearized sine-Gordon equation reproduces characteristic features of JPR in HI-BSCCO well. According to this equation, relation between three lengths L_1, L_2, and λ_c plays a key role to determine the ω_{cr}.

In summery, we study the Josephson plasma resonance (JPR) in $Bi_2Sr_2CaCu_2O_{8+y}$ with inhomogeneous phase coherence caused by partial introduction of columnar defects. We find the presence of a crossover frequency (ω_{cr}) at which the character of JPR changes from irradiated- to pristine-type. This result is in good agreement with that calculated from linearized sine-Gordon equation.

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