Novel Microwave Absorption Due to Strong Coupling between Josephson Plasma and the Josephson Vortex Array in Bi$_2$Sr$_2$CaCu$_2$O$_{8+\delta}$

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We have investigated the Josephson plasma excitations in magnetic fields parallel to the $ab$-plane in Bi$_2$Sr$_2$CaCu$_2$O$_{8+\delta}$ single crystals in a wide microwave frequency region (9.8 – 75 GHz). It was found that there are two kind of phase-collective modes: one increases with magnetic fields in higher fields, approaching linear asymptotic dependence with $ck$, which lies well above the inherent plasma frequency $\omega_p$, while the other does not show considerable field dependence. The higher linear mode is attributed to the Josephson plasma mode propagating along the reciprocal lattice vector of the Josephson vortex, whereas the lower one can be ascribed to the oscillation mode of Josephson vortices.

The interplay between the Josephson plasma (JP) and the Josephson vortex (JV), which is due to the linear and non-linear phase dynamics of the Josephson junction, has attracted much attention since the 1960s. In single junctions, the excitation spectrum has been investigated by Fetter and Stephen. They derived a gapless “vortex” mode attributed to the dc sliding of JVs and a “plasma” mode identical to the transverse JP, in which the propagation vector $k$ is equal to the reciprocal lattice vector of the one-dimensional JV array. The frequency of the traveling plasma wave can be controlled by the field parallel to the block (barrier) layer $H_\parallel$ according to the dispersion relation of the transverse plasma $\omega^2_p = \omega_p^2 \sqrt{1 + (ck)^2}$, where $\omega_p \equiv c/\sqrt{\epsilon \lambda_c}$ is the inherent plasma frequency, $c$ and $\lambda_c$ being the high-frequency dielectric constant and the penetration depth along the c axis. This plasma mode explains the so-called Ech resonance, which was found in the current–voltage ($I$–$V$) characteristics of Pb/PbO/Pb junctions, with the resonance voltage being proportional to $H_\parallel$.

In systems where the atomic-scale of weak Josephson junctions are stacking, namely an intrinsic Josephson junction (IJJ), which is realized in anisotropic high-$T_c$ superconductors represented by Bi$_2$Sr$_2$CaCu$_2$O$_{8+\delta}$ (BSCCO), the physics attributed to JP, JV, and their interplay are drastically richer. Because of the larger charge screening length ($\mu \approx 10$ Å) compared with the thickness of the CuO$_2$ bilayers ($t = 3$ Å), Josephson coupling between not only adjacent layers but also next-adjacent layers contributes to the transport along the $c$ axis. This longitudinal coupling yields the longitudinal JP mode propagating along the $c$ axis with a dispersion relation of $\omega^2_p = \omega_p^2 \sqrt{1 + \epsilon \mu^2}$ and rich variety of the dynamical nature of the two-dimensional JV lattice, which has been predicted by theoretical calculations and partly found experimentally.

So far, studies on the JP of high-$T_c$ superconductors in finite magnetic fields have concentrated on the case of the $c$ axis field, where vortices perpendicular to the layers can be regarded as static matter to suppress the Josephson coupling, representing fluctuations of pancake vortices. In contrast, in the field parallel to the $ab$ plane, vortices should be treated as dynamical matter because of the strong coupling between JP and JV. The microwave absorption associated with JP in the presence of JV is one of the key phenomena in revealing the linear and nonlinear dynamics of IJJ, which may also bring about high-frequency applications of high-$T_c$ materials.

In this letter, we describe the field dependence of the plasma frequency $\omega_p(H_\parallel)$ in fields parallel to the $ab$-plane through the Josephson plasma resonance (JPR) measurements as functions of the microwave frequency, field intensity, and temperature, in order to reveal the entire nature of JP in the presence of JVs. We obtained two resonance modes at higher and lower frequencies in good accordance with recent theoretical results. The higher-frequency mode, which increases in proportion with the field, is attributed to JP mode propagating along the primitive reciprocal lattice vector of the JV lattice, while the lower frequency mode, which depends only weakly on the field, is interpreted as the vortex oscillation mode modified by the vortex pinning and stacking effects of IJJ. This result explains the preliminary results of Matsuda et al., who have reported vanishing of the plasma resonance in fields very close to the $ab$ plane.

We have measured JPR in three BSCCO single crystals grown by the modified traveling solvent floating zone method. Two of the crystals were under-doped (U1, U2), while the other was optimally-doped (OP), with all having been obtained after appropriate annealing processes in controlled atmospheres. The superconducting transition temperatures $T_c$’s of these crystals were determined by magnetization measurements with a SQUID magnetometer as 70.2, 72.5, and 90.5 K for U1, U2, and OP, respectively. All JPR data displayed here were obtained in U1. JPR measurements were made in a microwave frequency range between 9.8 and 75 GHz, with both reflective and transmission-type bridge balance circuits with rectangular TE$_{102}$ mode cavity resonators. To selectively excite the longitudinal plasma mode only, the sample was placed inside the cavity so that the oscillating electric field parallel to the $c$-axis was exerted homogeneously over the $ab$-plane of the crystal. Frequency-stabilized microwaves were generated by the signal swept generator.
(HP83650B) or Gunn oscillators, and the resonance was detected by changes in the cavity impedance (Q-factor) by sweeping temperatures. The magnetic field was applied by a split-pair superconducting magnet, and the angle between field direction and the CuO$_2$ plane was adjusted by rotating the cavity resonator with respect to the magnet by a precision rotator. The alignment of the field direction exactly parallel to the $ab$-plane was determined from the symmetry of the angular dependence of the resonance within an accuracy of 0.01 degrees.

Figures 1 (a) shows the JPR absorption curves at 25.5 GHz obtained in various constant fields by sweeping temperature. Two clear resonance lines without hysteresis are found at higher and lower temperatures with a temperature gap in between. A sharp and symmetric resonance was observed just below $T_c$ in a low field region. With increasing fields, the higher temperature resonance mode shifts to lower temperatures below 1 kOe, then turns back to higher temperatures, and finally disappears above 1.5 kOe. In contrast, the resonance found at lower temperatures appears above 1.2 kOe. The resonance shifts to lower temperatures without a considerable change in its line-shape and intensity as the field is increased. The measurements with sweeping temperature at constant field were ideally reversible with well-defined low-resonance peaks at the higher temperatures and rather broad higher-field resonances at lower temperatures. We refer to the higher-temperature and lower-temperature resonances as HTB (higher temperature branch) and LTB peaks, respectively. That these two resonance branches are observed simultaneously and have different field dependences is peculiar to JPR in $H \parallel ab$ and is in sharp contrast to JPR in $H \parallel c$, where one resonance line whose resonance field monotonically decrease with temperature is observed in the configuration of the longitudinal excitation.

To study the doping dependence of these features, we performed similar measurements in crystals OP and U2. The JPR results at $\omega/2\pi = 42$ GHz in OP were found to be qualitatively similar to the ones at 19 GHz in U1, although the resonance temperatures and fields were different. This similarity can be understood by considering the frequency ratio of $\omega/\omega_p$, which is less than one and closer to unity in more under-doped crystals for a given $\omega$ because $\omega_p$ is lower in higher anisotropic crystals. Provided that 19 GHz in U1 and 42 GHz in OP give the same $\omega/\omega_p$ value, we derive $\omega_p$ of OP as 130 GHz, which is a typical plasma frequency for optimally doped BSCCO. Here, we used $\omega_p$ of U1 as 56.8 GHz, as described below. This scaling is also valid for results in U2, with slightly
higher doping than U1. Therefore, the resonance splitting is observed at \( \omega > \omega_p/3 \), and the magnitude of the temperature gap between LTB and HTB is larger at \( \omega \), being closer to \( \omega_p \). In contrast, \( \omega \) is much smaller than \( \omega_p \), LTB merges to HTB as observed at 9.8 GHz in U1, resulting in a single branch. This is the reason why Matsuda et al. did not observe vanishing of the resonance in an optimally doped crystal in Ref. 2.

The resonance peaks of LTB and HTB as a function of magnetic fields for various frequencies are plotted in Fig. 2 (a) and (b), respectively. With increasing frequency, both LTB and HTB shift to lower temperatures. Because the decrease of LTB is larger than the one of HTB, LTB goes above our experimental temperature range above 30 GHz, whereas HTB could be observed throughout the temperature range below 60 GHz. The JPR can be clearly observed even in zero magnetic field, as seen in Fig. 2 (a). This zero-field resonance occurs at a particular temperature \( T_0 \) and at a corresponding microwave frequency. The frequency dependence of \( T_0 \) has been reported previously and has been explained by using a simple two-fluid model with a temperature-independent scattering rate. By extrapolating the temperature dependence of the plasma frequency \( \omega_p(T) \) to \( T = 0 \), the inherent plasma frequency \( \omega_p \) is estimated to be 56.8 GHz, which yields \( \lambda_c = 217 \mu m \) with \( \epsilon = 15 \).

The bending-over behavior of HTB becomes greater at higher frequencies, and the JPR above 30 GHz extends to temperatures even higher than \( T_0 \). This surprising behavior is certainly beyond our current understandings of JPR in perpendicular fields, where the plasma frequency should decrease both with application of high magnetic field and with increasing temperature because of the suppression of the interlayer coherence \( \langle \cos \varphi_{l,l+1}(H,T) \rangle \) in response to the fluctuation of pancake vortices. Above 1.5 kOe, HTB obtained at higher frequencies lies at higher fields at the given temperatures, suggesting that the HTB resonance can be observed even above \( \omega_p \). As shown in Fig. 2 (b), at 74.8 GHz where no JPR can be observed in the case of \( H \parallel c \), we detected a clear resonance. This resonance shows a remarkable angular variation and therefore can be found only within \( \pm 3 \) degrees of the \( ab \)-plane above 3 kOe. The resonance field of this JPR mode shifts to high fields as the temperature is increased and finally disappears above approximately 5 kOe. A similar resonance was obtained at another three frequencies above \( \omega_p \) (61.7, 65.9, and 74.3 GHz). These are plotted in Fig. 2 (b).

In Fig. 2 (a), the frequency-field diagrams extracted from Fig. 2 are shown. It is clear that there are two resonance modes well-separated by a frequency gap. The higher one extracted from HTB shows an upturn at approximately 1 kOe, then monotonically rises to higher frequencies even above \( \omega_p \), while the lower one extracted from LTB shows a gradual decrease with increasing field. Because LTB can be observed only in a finite field, the existence of JVs is considered to be required for LTB. At low fields below 0.5 kOe, the extrapolation of LTB to low fields tends to approach zero frequency, suggesting that LTB may be in a gapless mode at the zero-field limit. From these considerations we attribute LTB and HTB to the vortex and plasma branches as suggested in Ref. 3.

Recently, Bulaevskii et al. has proposed a qualitative picture of the plasma resonance in a layered superconductor on the basis of the single junction model. With increasing parallel field \( H_\parallel \), the frequency of the plasma resonance increases while the resonance intensity decreases because of the decrease in the optical weight of the plasma, and the resonance finally disappears in the high field limit \( H_\parallel \gg H_0 \equiv \Phi_0 / \gamma s^2 \), where \( \Phi_0 \) is the flux...
quantum and $s$ is the interlayer spacing. In contrast, the vortex resonance survives even in $H_{||} \gg H_0$ and lies at a non-zero frequency by introducing periodic pinning of JVs. Thus, we attribute HTB and LTB to the plasma oscillation and the oscillation of JVs.

Quite recently, Koshelev and Machida have derived absorption spectra of the JP mode in a layered superconductor in high parallel fields, with a uniform oscillating electric field being applied parallel to the $c$-axis. Assuming that all block layers are fully occupied by JVs forming a distorted triangular lattice according to the anisotropy, they analytically and numerically calculated the dispersion relation and absorption spectra of the JP mode. Because the periodicity of the JV lattice induces a modulation of the interlayer phase difference, the $\mathbf{k}$-vector of the JP mode corresponds to the primitive reciprocal lattice vector of the JV lattice $\mathbf{q}$, which consists of the $c$-axis component $q_z$ fixed on $\pi/s$ due to the intrinsic pinning and the $ab$-plane component $q_{ab}$ proportional to the magnetic field $H_{||}$ as $2\pi s H_{||}/\Phi_0$, as depicted in Fig. 2 (b). Therefore, a tilted JP wave as a mixture of the longitudinal plasma with $k_z = q_z$ and the transverse plasma with $k_{xy} = q_{ab}$ can be excited. The plasma frequency is determined by the dispersion relation along $q$ lying between the longitudinal and transverse plasma modes and rises with magnetic field because of the linear increase in $q_{ab}$. It should be noted that the dispersion is very close to the longitudinal dispersion for $q_{ab} \ll q_z$. As a result, the peak frequency of the dissipation spectrum, corresponding to the resonance peak, is proportional to $H_{||}$ in high fields as

$$\omega_p(H_{||}) = \frac{\pi H_{||} \gamma s^2}{\Phi_0}.$$ \hspace{1cm} (1)

Assuming that $\gamma = 1070$, a value that is quite reasonable for under-doped BSCCO samples, this equation provides a good agreement with the experimental data above 3 kOe at all temperatures, as shown in the inset of Fig. 3 (a), where we used $s = 15$ Å. It should be noted that this equation has been derived in Ref. 4. In this situation, all block layers are expected to be occupied by JVs above $H^* = \Phi_0/4.6 \gamma s^2$, which is estimated to be 2.1 kOe for $\gamma = 1070$. This value is consistent with the fact that the linear field dependence of HTB is violated below 3 kOe, as shown in Fig. 3 (a). We therefore conclude that the linear increase in $\omega_p(H_{||})$ of HTB is due to the increase in $q_{ab}$ of the JV lattice, while $q_z$ is fixed on $\pi/s$ because of the triangular lattice. This result suggests that the excited plasma frequency can be easily controlled by adjusting the magnetic fields parallel to the layers even above $\omega_p$.

The absorption intensity of the HTB resonance is thought to be diminished as frequency is increased because the intensity is weaker at higher temperature and higher frequency. This diminishing is predicted due to the increase in the quasiparticle damping along the $c$-axis, which is directly connected to the tunneling mechanism of high-$T_c$ superconductors. As discussed previously, the higher quasiparticle conductivity along the $c$-axis broadens the resonance line and weakens the resonance intensity.

The origin of the intensity of the vortex resonance (LTB), which is comparable to the plasma resonance in our experiments, has not been conclusive, although a much weaker absorption below $\omega_p$ was obtained by numerical calculations in a single junction model in which the randomness of the critical Josephson current along the layer was introduced. The frequency obtained in the calculations is much lower than the experimental results. This discrepancy can be attributed to the pancake pinning yielded by misalignments of magnetic fields and thermal fluctuations as predicted by Sonin.

The initial decrease in HTB frequency with increasing field below 3 kOe cannot be explained by their approach, which may in part be due to the thermal fluctuation of JVs because the slope is larger at higher temperatures. Furthermore, it may be important to note that in the strongly coupled region JV lattice and JP soliton-like wave excitations as well as continuous waves are expected as described above. Further study is needed to obtain better understanding of these complicated dynamical behaviors.

In summary, we have for the first time found two microwave excitation modes with a temperature-dependent gap in parallel magnetic fields of BSCCO. Strong coupling between JP and the JV lattice are responsible for these two modes. We have concluded that in high fields where all block layers are occupied with JVs, one lying at higher frequencies comes from the JP wave propagating in a tilted direction with respect to the JV lattice structure, while the other seems to originate from the oscillation of the Josephson vortices.

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