Resonant terahertz radiation from Tl$_2$Ba$_2$CaCu$_2$O$_{8+\delta}$ thin films by ultrafast optical pulse excitation

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We have observed the free-space radiation of the resonant terahertz wave from c-axis oriented Tl$_2$Ba$_2$CaCu$_2$O$_{8+\delta}$ thin films by femtosecond optical pulse excitation under a radial magnetic field of about 100 Oe parallel to the c axis of the thin film. The observed wave form showed clear oscillations up to 80 K. The frequency was shifted from $\sim$ 620 GHz at 24 K to $\sim$ 300 GHz at 80 K, corresponding to an increase in c-axis penetration depth, $\lambda_c$, from $\sim$ 26 $\mu$m to $\sim$ 53 $\mu$m, and disappeared above $T_C$ as expected for the Josephson plasma resonance. © 2002 American Institute of Physics. [DOI: 10.1063/1.1475770]

Since the discovery of terahertz (THz) pulse radiation from photoconductive switching semiconductor device by femtosecond optical pulse (FOP) illumination by Auston et al., THz pulse radiation phenomena from several kinds of materials have been discovered. These materials have been used as an effective radiation source of THz wave to investigate the high-frequency properties of a variety of materials. THz radiation from semiconductors is well established and explained by photoexcitation of carriers followed by ultrafast modulation of photocurrent and locally induced polarization. The ultrashort time scale (1 picosecond) of modulation of photocurrent gives rise to the THz pulse radiation.

The current-biased high-$T_C$ superconductors (HTSC), YBa$_2$Cu$_3$O$_{7-\delta}$ (YBCO), and Bi$_2$Sr$_2$CaCu$_2$O$_{8+\delta}$ (BSCCO) thin-film bridges, also radiate THz pulses due to ultrafast supercurrent modulation in the non-equilibrium state of superconductivity induced by FOP excitation. However, the detailed properties of the THz wave form were found to be quite different for YBCO and BSCCO. The effective Fourier components of the THz pulse from BSCCO were lower than 0.2 THz, while characteristically lower than 2 THz for YBCO.

On the other hand, it has been theoretically predicted that strong THz resonant wave could be radiated from HTSC by collective excitation due to Josephson plasma resonance (JPR). A lot of experimental effort has been made to realize free-space radiation of coherent THz wave by the JPR phenomena. Concerned with the JPR phenomena, the difference in the effective maximum frequencies for BSCCO and YBCO may be due to the difference in the resonant frequency of JPR, as the JPR frequency of YBCO is much higher than that of extremely anisotropic BSCCO. However, we cannot reach a final conclusion about these materials because of the limitation in the effective frequency ranges of the THz detector (0.2–1.5 THz) of our system. Tl-based cuprate superconductors are a good candidate to investigate the relation of THz radiation by supercurrent modulation to the JPR, because the resonant frequency of JPR for Tl-based cuprate superconductors is about 700 GHz at low temperatures, which corresponds to the most sensitive frequency range of a photoconductive switching device as a THz wave detector. In this letter, we report the properties of THz radiation emitted from c-axis oriented Tl$_2$Ba$_2$CaCu$_2$O$_{8+\delta}$ (TBCCO) thin films by FOP excitation. As a result, we observed a resonant THz wave radiation besides the THz pulse radiation due to supercurrent modulation, if we apply a magnetic field below $T_C$.

The TBCCO thin film of about 220 nm in thickness was prepared on a (1102) sapphire substrate by a two-step magnetron sputtering method with the intermediating CeO$_2$ buffer layer of about 55 nm in thickness. The thin film has a critical temperature $T_C$ of 99 K, and a critical current density $J_c$ of about 2 MA/cm$^2$ at 77 K. To investigate THz wave radiation properties, the film was patterned into a bow-tie antenna structure with a bridge of 30$\times$40 $\mu$m$^2$ (width $\times$ length) in the central part by means of photolithographic techniques. THz radiation properties were observed by FOP excitation to the TBCCO bow-tie antenna with applying bias current or an external radial magnetic field. The detailed experimental procedures have been reported elsewhere.

Figure 1 shows a typical THz wave form emitted from a TBCCO thin film by FOP excitation at the laser power of 6 mW applying a radial magnetic field of about 100 Oe nearly parallel to the c axis of the thin film. The radial magnetic field was applied by using a permanent magnet ring. The leading pulse around 11 ps followed by the resonant oscillations can be seen in Fig. 1.
tions under magnetic field became narrower with increasing laser power (see Fig. 3). The inset in Fig. 1 shows a typical wave form emitted from the TBCCO bow-tie antenna with the bias current of 50 mA under zero-field condition. In this case, we observed only a single THz pulse similar to that from YBCO and BSCCO with bias current, and could not see clearly resonant oscillations as observed under a magnetic field. The wave form observed under a magnetic field is quite different from that with bias current. Noted is that under the magnetic field, the oscillation lasts for about 10 ps which just corresponds to the period of a single THz pulse emission from the current biased TBCCO. It indicates that the resonant THz wave radiation is closely related to the ultrafast modulation in the eddy currents around the vortices.

To investigate the detailed properties of THz wave forms emitted from TBCCO, the Fourier components were obtained through a fast Fourier transformation (FFT) of the wave form. Figure 2 shows the FFT spectra obtained from the wave forms. The dotted line in Fig. 2 shows the FFT spectrum obtained for the current biased TBCCO at 24 K. The solid lines show the FFT spectra obtained under an applied magnetic field at several temperatures, and these were calculated from the oscillating data in the wave forms (from 10 to 20 ps in Fig. 1). The dotted line shows the central frequency of ~100 GHz with the cutoff frequency of ~700 GHz. The central frequency corresponding to the peak was temperature independent. This Fourier spectrum indicates the radiation properties similar to that of YBCO and BSCCO, although the central frequency is different. While, the solid line in Fig. 2 at 24 K shows, besides the peak around ~100 GHz as shown in the dotted line, an additional peak around 620 GHz due to the resonant oscillations, with the cutoff frequency of ~700 GHz. The frequency of the additional peak is related to the frequency calculated from the period of resonant oscillations at each temperature (represented as arrows in Fig. 2). The additional peak shifted toward the lower frequency region with increasing temperature and vanished above \( T_C \). These results show the close relation between the cutoff frequency of the THz pulse due to ultrafast supercurrent modulation and the resonant oscillation. It also indicates the possibility of the electromagnetic wave absorption due to JPR phenomena for the current-biased TBCCO. Furthermore, it is noted that the additional peak in the FFT spectrum does not indicate any absorption rather a substantial radiation of resonant THz wave into free space.

Figure 3 shows the temperature dependence of the frequency of the additional peak at the respective laser powers of 2 mW and 6 mW. It can be seen that the frequency shifts toward lower frequency regions with increasing temperature (some of FFT spectra at different temperatures are also displayed in Fig. 2), and disappeared above \( T_C \), although the peak around 100 GHz remains temperature independent till it disappeared above \( T_C \), too. Oscillation frequency also tends to decrease with increasing excitation laser power. Noted is that a markable decrease in oscillation frequency can be seen at \( \sim 45 \) K with increasing temperature. It may be attributed to the transition from the vortex solid state to the pancake liquid state.18

As shown, the resonant THz wave emitted from TBCCO under a radial magnetic field is apparently different from that observed under bias current condition. One possible reason for the resonant oscillation is due to the JPR. In the small radial magnetic field condition, the vortices are expected to penetrate into the film forming a vortex lattice in stairs structure due to the tilted elements of radial magnetic field. However, the vortex solid state is easily fluctuated by the FOP illumination, as the ultrafast modulation occurs in the eddy currents around the vortices. Under this transient condition induced by FOP illumination, a strong correlation could be expected between the electric field emitted due to the eddy-current modulation and the fluctuating in-plane vortices, and a resonant THz wave would be radiated due to the JPR phenomena.
results show the possibility to develop a tunable THz wave source acting at sub-THz regions by applying the photomixing technique to excite the resonant phenomena.\textsuperscript{22,23}\ As for the observed resonant THz wave, the observed behavior is quantitatively explained by the JPR phenomenon. However, further investigations are necessary to get more detailed information on magnetic field and temperature dependence of the resonant THz wave.

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