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Emission Properties of YBCO-Film Photo-Switches as THz Radiation Sources

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Subpicosecond electromagnetic pluses were generated from biased YBCO-film photo-switches by exciting with fsec laser pulses. The radiation has a very broad spectrum extending up to 2 THz. The pulsed THz radiation originates from the ultrafast supercurrent modulation induced by breaking of Cooper pairs due to the photon absorption and indicates ultrafast response of the high T_C superconductor. The YBCO-film photo-switches were characterized as a radiation source by measuring the pump power, bias current, and temperature dependence of the radiation amplitude.

1. INTRODUCTION

Generation of THz electromagnetic wave pulses (THz radiation) by excitation of photoconductive switches with short laser pulses has been studied extensively in the last decade. The photoconductive materials used in the photoconductive devices reported so far were high-speed semiconductors, such as the radiation damaged silicon on sapphire substrate[1)] or the low-temperature grown GaAs (LT-GaAs) epitaxial film[2)]. For the semiconductor-based photoconductive switches the origin of THz radiation is the ultrafast current modulation due to the laser induced photocarriers. Recently our group has reported generation of THz radiation from a biased high-T_c superconducting (HTS) photo-switch.[3,4)] The HTS photo-switch was a $YBa_2Cu_3O_{7-\delta}$ (YBCO) film shaped in a small dipole antenna. In the case of HTS photo-switch the radiation originates from the ultrafast supercurrent modulation by the femtosecond laser pulses: The laser pulses break the supercarriers (Cooper pairs), and the supercurrent is modulated in sub-picosecond time-scale causing the emission of the THz radiation. In this paper we report a detailed study on the emission properties of HTS photo-switches by measuring the dependence of radiation amplitude on the pump power, the bias current and the temperature.

2. EXPERIMENT

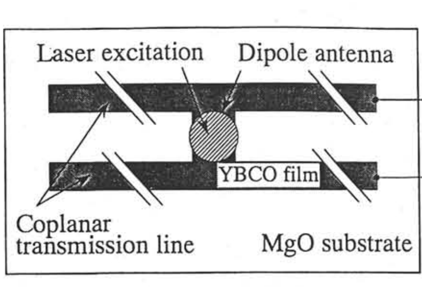

Figure 1. Schematic structures of a high-T_C superconducting photo-switch.

Thin films of YBCO have been deposited on 0.5-mm-thick MgO(100) substrates by eclipse pulse laser deposition. The films were c-axis oriented, and the thickness of the films was 140-200 nm. The critical temperature (T_C) of the films was about 80 K. The YBCO-film photo-switch consisted of a coplanar transmission line with 30 μm in width and 6mm in length, and a 20x20 μm bridge structure at the center of the transmission line (Fig. 1), which was patterned into the YBCO film using standard photolithographic techniques and a wet chemical etch. The experimental setup is illustrated in Fig. 2. A mode-locked Ti: sapphire laser operating at a repetition rate of 82 MHz was used to generate 80-fsec light pulses at a wavelength of about 800 nm. The laser beam was focused into 20-30 μm in diameter on the center of the bridge, which acts as a small dipole antenna. The radiation was detected by a photoconductive dipole antenna fabricated on an LT-GaAs film having a carrier lifetime of 300 fsec. The photoconductive detector was gated by the probe pulses separated from the pump pulses, and was sensitive to the radiation electric fields only during the photo-excited carriers were alive. The time-resolved waveform of the radiation was obtained by changing the delay between the

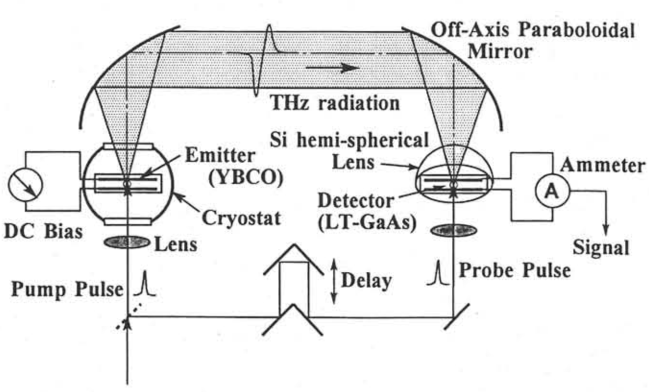

Figure 2. Experimental setup for detection of the THz radiation from the HTS photo-switch.

pump pulses and probe pulses. The HTS photo-switch was mounted on a cold finger of a cryostat with a 3-mm thick fused quartz window.

3. RESULTS AND DISCUSSION

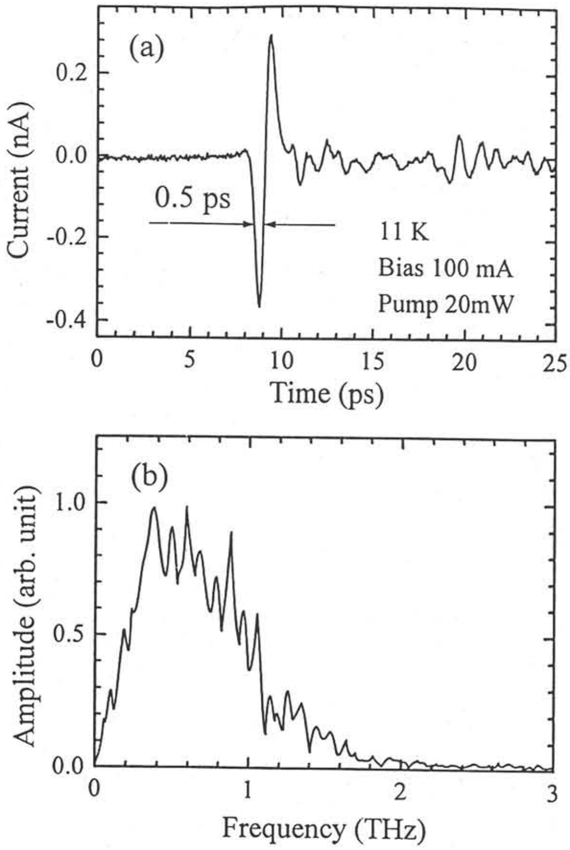

Fig. 3. **(a)** Waveform of THz radiation from a YBCO photo-switch detected by a photoconductive dipole antenna. **(b)** The Fourier transformed amplitude spectrum of the waveform (a).

Figure 3(a) shows the observed waveform of the THz radiation from a YBCO photo-switch at 11 K. The bias current and the pump laser power were 100 mA and 20 mW, respectively. A sharp pulse of 500 fsec in width is observed. The modulation on the signal after the main pulse is due to the strong absorption of water vapor in the air. Since in the radiation theory for a small dipole the radiated electric field is proportional to the time-derivative of the modulated current, the first negative peak is interpreted to correspond to the sudden reduction of supercurrent and the subsequent positive peak to the recovery of the supercurrent. We attribute the reduction of the supercurrent to the breaking of the Cooper pairs and excitation of hot quasi-particles by the absorption of the infrared photons (E=1.55 eV), and also to the subsequent avalanche-excitation of quasi-particles by the hot quasi-particles through electron-electron interaction or electron-phonon interaction. The sharp positive peak implies ultrafast recombination of the quasi-particles ($\tau < 1$ ps). A detailed discussion on the carrier dynamics based on the phonon-quasi-particle interaction will be given elsewhere.[5]

Figure 3(b) shows the amplitude spectrum obtained by a numerical Fourier transformation of the waveform in Fig. 3(a). The spectrum extends up to 2 THz with its peak at 0.5 THz. The bandwidth is comparable to that obtained for the semiconductor-based photoconductive switches with similar structures.

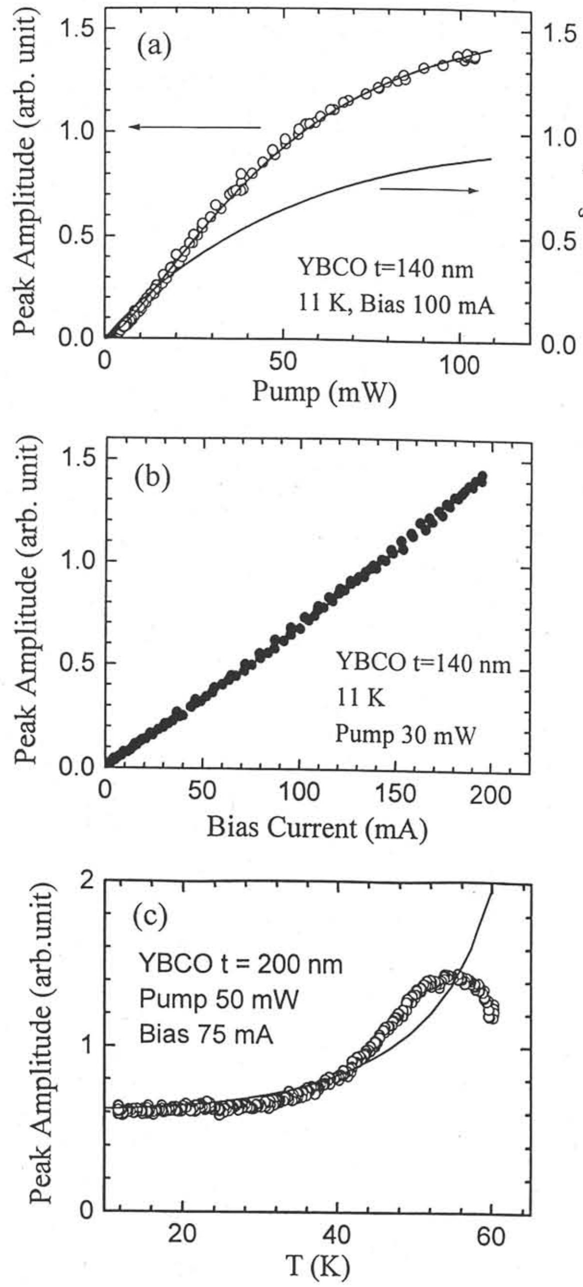

Fig. 4. The dependences of the THz radiation amplitude on **(a)** the pump laser power (at 11 K and a bias current of 100 mA), **(b)** the bias current (at 11 K and a pump power of 30 mW), and **(c)** the temperature (with a pump power of 50 mW and a bias current of 75 mW).

The pump-laser power and the bias current dependence of the radiation amplitude at the peak were measured at 11 K, and the results are shown in Fig. 4(a) and 4(b), respectively. The radiation amplitude increases super-linearly against the pump power in the relatively weak excitation region and show a saturation tendency in the strong excitation region (Fig. 4(a)). The bias current dependence in Fig. 4(b) shows an almost linear increase of the radiation amplitude against the bias current, but a slight deviation from linearity is observed in the high bias region. The radiation amplitude from a small dipole is proportional to the amplitude of current modulation, which is expected to be linear against the peak intensity of the pump laser pulses and the bias current for the HTS photo-switches. Thus we expect a linear increase of the radiation amplitude against the pump laser power and the bias current. Before discussing the deviation from the linear dependence of radiation amplitude on the pump power or bias current, we should note that only very small portion of the radiation generated within the YBCO film is emitted out into the air. An estimation indicated only 0.1 or 0.2 % of the radiation generated within the film can be transmitted to the air due to the very high refractive index ($\tilde{n} = n - i\kappa$; $n, \kappa >> 1$) of the YBCO film. In other words, there is a very large impedance mismatch between the YBCO film and the air. In general, the refractive index of the superconducting material decreases with decreasing supercarrier density n_S. The super-linear increase of the radiation amplitude at moderate excitation thus can be attributed to increase of the transmission due to transient reduction of n_S by the laser excitation and/or reduction of n_S due to heating. The saturation observed at higher pump intensities might be caused by depletion of supercarriers. An estimation assuming an avalanche-excitation indicated that an order of 10^{21} cm^{-3} quasi-particles are excited at a pump power of 100 mW, which is close to the total carrier density $n = 2\text{-}6\times10^{21}$ cm^{-3}.

The super-linear dependence of the radiation amplitude on the bias current is also explained by decreased supercarrier density caused by heating at higher bias currents, where the YBCO film became slightly resistive.

We also measured the temperature dependence of the radiation amplitude. Figure 4(c) shows the dependence of the radiation amplitude on the temperature for a 200 nm-thick sample under a constant pump (50 mW) and bias (75 mA) condition. The radiation amplitude increase with increasing temperature and take a peak at T=55 K, and then decrease with temperature. Above 60 K it was not possible to keep a constant bias current. The increase of radiation amplitude with increasing temperature can also be explained by the increased transmission of radiation generated in the YBCO film due to the reduction of n_S at higher temperatures.

The frequency- and temperature-dependent refractive index $\tilde{n}(\omega, T) = n(\omega, T) - i\kappa(\omega, T)$ can be calculated by using the two-fluid model from the temperature-dependent supercarrier density $n_s(T)$ and the quasi-particle scattering time $\tau(T)$. By using $n_s(T)$ and $\tau(T)$ measured at a microwave frequency (ω=140 GHz),[6] we calculated the temperature-dependent $\tilde{n}(T)$ at 500 GHz, where the spectrum of the THz radiation takes a maximum amplitude. Using this $\tilde{n}(T)$, we calculated temperature-dependent transmission efficiency for 500-GHz radiation with an assumption that a plane-wave radiation generated in the middle of the film thickness travels through the film and is transmitted to the free space. The result is shown in Fig. 4 by a solid line. The theoretical curve was fitted to the experimental data at low temperatures and the sample temperature was assumed to have increased effectively by 20 K by the laser excitation. The qualitative agreement between the calculation and the experimental data support our interpretation about the temperature-dependent radiation amplitude.

The pump-power dependent transmission efficiency can also be calculated by assuming the transient change of supercarrier density caused by the pump pulses. The emission amplitude of THz radiation then is expected to be proportional to the pump intensity I_p multiplied by the transmission efficiency. In order to consider saturation property at high pump intensities we assumed a excitation function for the transient change of the supercarrier density $-\delta n_s/n = \delta n_n/n = \delta n_n/(n_s + n_n) = 1 - \exp(-\alpha I_p)$, where n_n is the normal carrier density and α is a constant associated with the generation rate of normal carriers. Based on the above assumption we calculated pomp-power dependent emission amplitude by taking α as a fitting parameter. The result is shown in Fig. 4(a) by a solid line, for which α was set to 2.0/100 mW, and the $\delta n_n/n$ was also shown in Fig. 4(a). Our calculation reproduced well the experimental result, implying the super-linear increase of the radiation amplitude at low pump intensities was due to the change of transmission efficiency caused by the transient supercarrier density.

4. CONCLUSIONS

In conclusion we investigated the THz emission properties of YBCO-film photo-switches by measuring the pump, bias, and temperature dependence of the radiation amplitude. It was shown from our model calculations that the super-linear increase of the radiation amplitude against the pump intensity can be explained by the increased transmission efficiency of the radiation from the YBCO film to the air, which was caused by the transient reduction of supercarrier density induced by pump pulses. It was also shown that the temperature dependence of the radiation amplitude is explained by the reduced supercarrier density and the resultant increase of transmission efficiency of the radiation with increasing temperature, except the decrease of the radiation amplitude near T_C.

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