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Investigation of the electrical field sensitivity of sub-µm Y-Ba-Cu-O detectors

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***Abstract*—The behavior of sub-µm-sized thin-film $YBa_2Cu_3O_{7-x}$ (YBCO) detectors under illumination with picosecond terahertz (THz) pulses was investigated. Real-time measurements with a temporal resolution of 15 ps full width at half maximum (FWHM) were performed at ANKA, the synchrotron facility of the KIT, and the UVSOR-III facility at the Institute of Molecular Science in Okazaki, Japan. The capability of YBCO detectors to reproduce the shape of a several picoseconds long THz pulse was demonstrated. Single-shot measurements adhering to a reversal of the direction of the electrical field of the THz radiation were carried out. They provided evidence for the electrical field sensitivity of the YBCO detector. Exploiting the electrical field sensitivity of the YBCO detector the effect of microbunching was observed at UVSOR-III.**

***Index Terms*—Yttrium barium copper oxide, electrical field sensitivity, THz detectors, Zero-bias detection, synchrotron radiation.**

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I. Introduction

THE PHOTORESPONSE of the high-temperature superconductor $YBa_2Cu_3O_{7-x}$ (YBCO) to optical and infrared wavelengths has been studied comprehensively in the 1990s, [1] - [3]. Considering the superconducting energy gap of YBCO of $2\Delta \approx 20$ meV [4], the photon energy then corresponds to an above-gap excitation. The detection of above-gap photons by bolometers made of thin YBCO films can be well described by heating of electrons in the frame of the two-temperature model [5]. The corresponding energy relaxation times in YBCO have been measured and are in the sub-picosecond and picosecond range for electron-electron and electron-phonon interaction respectively ($\tau_{ee} = 0.56$ ps, $\tau_{e\text{-}ph} = 1.1$ ps) [3]. Operation of hot-electron bolometers always requires a bias current in order to measure variations of the electron temperature caused by absorbed power. However, additional contributions of vortices to the YBCO detector response for above-gap excitations have been considered [6], [7].

The mechanism of detection of radiation in the terahertz (THz) frequency range differs significantly. The THz photon energy corresponds to a sub-gap excitation of YBCO (e.g. f = 1 THz equals to a photon energy of $E_\gamma = 4.1$ meV). Therefore breaking of Cooper pairs in YBCO due to the absorption of photons with energies up to a few THz is unlikely. Ilin *et al.* investigated sub-gap continuous wave excitations of YBCO detectors and found that the detector's response could not be sufficiently explained by the two-temperature model [8]. They proposed vibrating vortices inside the YBCO detector as a competing detection mechanism. Probst *et al.* first showed that the direct response of a YBCO detector to pulsed THz radiation near T_c differs from the above-gap regime in regard to pulse shape, bias current and radiation power dependence [9]. The nanosecond-scaled bolometric response does not occur in the THz frequency range where only a fast picosecond pulse is measured. Moreover, the detector response depends linearly on the bias current contrarily to the optical frequency range where the same detector shows quadratic dependence as to be expected from a bolometer. The observed behavior was accounted for the dissipative movement of vortices through the YBCO detector. Thus THz radiation generates an rf current through the detector when absorbed by a dedicated THz antenna. This current, when

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exceeding the critical current for vortex penetration, will generate vortices which then rearrange into a vortex line [10]. Vortices moving with their critical velocity v_c through that channel generate an electrical field that causes a voltage pulse across the YBCO detector. The critical velocity, v_c, depends on the inelastic scattering time which corresponds to the electron-phonon interaction. Thus, the response times are in the picosecond range. Response times, limited by the bandwidth of the rf readout, of down to 16 ps full width at half maximum (FWHM) have been demonstrated [11]. The displacement of vortices generates a measureable voltage pulse across the detector even in absence of an externally applied bias current. Zero-bias detection could thus be demonstrated with a YBCO detector in the THz frequency range [9]. The direction of movement of the vortices through the YBCO detector depends on the direction of the current generated by the THz photons. Therefore, when operating the detector at zero-bias conditions an electrical field sensitivity should be observed rather than an intensity sensitivity.

Investigations based on picosecond THz pulses first became feasible with the discovery of the so called Coherent Synchrotron Radiation (CSR) [12]. Very short electron bunches in a synchrotron or short substructures in longer bunches emit THz pulses of high brilliance with pulse durations down to the sub-picosecond range and a broad-band spectrum ranging from a few GHz up to approximately 2 THz [13], [14]. The detailed analysis of the coherent THz emission, microbunching and other CSR related effects for improvement and further development of synchrotrons requires electrical field sensitive detectors with picosecond time resolution.

This report focuses on the demonstration and investigation of electrical field sensitivity of YBCO detectors based on single-shot THz measurements. We present the fabrication of the YBCO detectors in Section II and the experimental setup in Section III, where we also emphasize why single-shot measurements are required. Sections IV and V concentrate on experiments performed at the synchrotron sources ANKA and UVSOR-III, respectively. We present an experimental setup for the ANKA facility that allows for the investigation of electrical field sensitivity even though the shape of consecutive CSR pulses is changing (Section IV). Electrical field sensitivity at zero bias conditions of the YBCO detector allowed for the investigation of the microbunching phenomenon at UVSOR-III (see Section V).

II. Fabrication of YBCO detectors

A. *Thin-film deposition*

An epitaxial thin-film multilayer was deposited on top of both-side polished *R*-plane sapphire. Due to the low intrinsic losses of the substrate in the THz frequency range ($\varepsilon_r = 10.06$, $\tan\delta = 8.4\cdot10^{-6}$ at 77 K, [15]) back-side illumination of a YBCO detector grown on top of sapphire is feasible. For the epitaxial growth of the thin films a pulsed-laser deposition at a temperature of 800°C is used. To compensate the lattice mismatch of 12% between sapphire and YBCO additional buffer layers are necessary [16]. A CeO_2 buffer layer of 10 nm

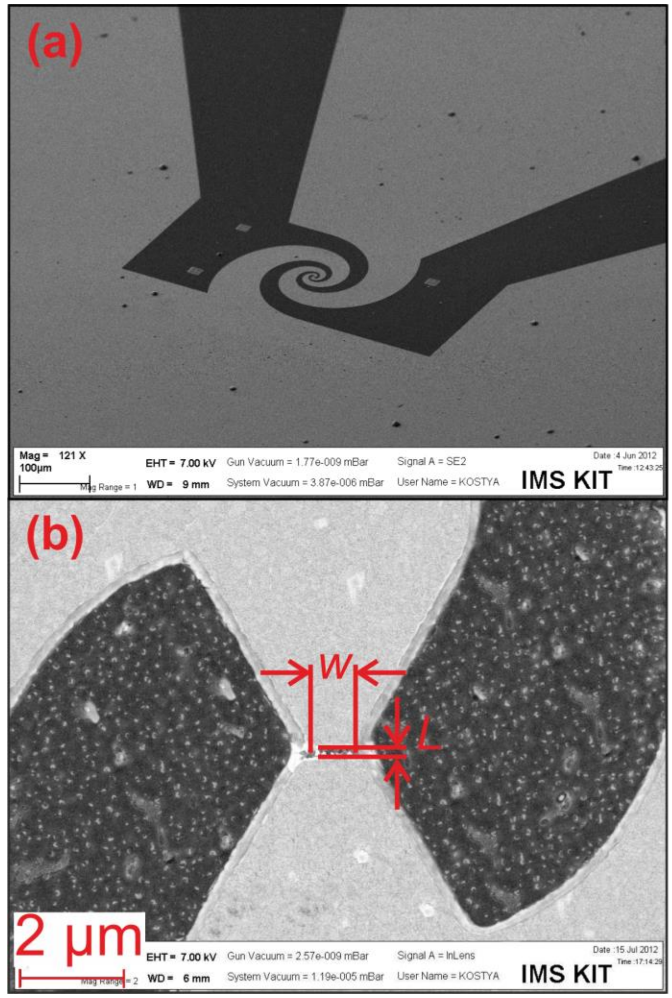

Fig. 1. (a) SEM image of the log-spiral broad-band antenna and the coplanar waveguide. (b) Sub-µm-sized detecting element of detector N° 3 embedded into planar antenna. Dimensions can be found in Table 1. Gold appears in light grey, the sapphire substrate in dark grey.

thickness and a 30 nm thick $PrBa_2Cu_3O_{7-x}$ (PBCO) layer were deposited in-situ before growing the 30 nm thick YBCO film. A second 30 nm thick PBCO layer was then deposited in order to protect the underlying YBCO during patterning of the detector. After annealing in oxygen of the multilayers, a 150 to 200 nm thick gold film was deposited on top. The in-situ deposition of gold ensures a low contact resistance between the YBCO detector and the readout contacts.

B. *Patterning procedure*

After deposition of the thin films, two lithography and etching steps were carried out. To remove the gold on top of the active detecting element a slit was defined in the resist using electron-beam lithography (EBL). The width of the slit herein presets the length *L* of the detector. The gold was then removed by ion-beam etching (IBE) and subsequent wet-chemical etching with a $I_2(KI)_5$-solution. Both etching techniques entail advantages. IBE allows for the easy definition of sub-µm structures due to its anisotropy. However, due to ion implantation and heating of the sample a complete removal of the gold by IBE would degrade the superconducting properties of the YBCO detector. Wet-

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TABLE I
YBCO DETECTOR PROPERTIES

Det. N°	Width w (µm)	Length L (µm)	Critical Temperature T_c (K)	Critical current Density at 77 K j_c (MA·cm^{-2})
1	0.91	0.30	83.0	3.7
2	4.50	2.00	85.3	4.9
3	1.04	0.21	83.1	3.2
4	1.52	0.37	84.6	4.5

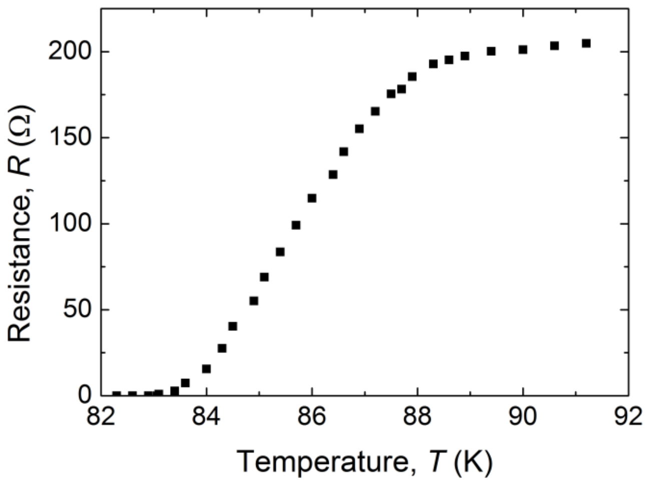

Fig. 2. Temperature dependence of resistance of detector N° 3.

chemical etching does not harm the PBCO and YBCO layers but enlarges the detector slit due to isotropic etching of the gold. By combining both etching techniques and removing only a 30 to 40 nm thick gold layer directly on top of PBCO by wet-chemical etching a minimal length of L = 200 nm can be achieved. Based on a second EBL step the width w of the detecting element as well as the antenna and broad-band coplanar readout design of the YBCO detector are defined. The patterning is again realized with IBE. Fig. 1(a) shows the planar antenna embedded in the planar coplanar waveguide for readout with 50 Ω impedance. The bandwidth of the log-spiral antenna ranges from 150 GHz up to 2.5 THz [9]. Fig. 1(b) shows the detecting element in the center of the antenna. The dimensions of the four detectors employed in the context of the presented measurements are listed in Table I. The thickness of the YBCO layer remains constant for all detectors, d_{YBCO} = 30 nm. A more detailed description of the thin-film deposition and the pattering of the YBCO detectors can be found in [17].

C. DC Characterization

In order to determine the superconducting properties of the YBCO detectors they were mounted inside a cryogen-free cooler with an adjustable temperature range from 50 K up to 300 K. Fig. 2 shows the transition of the sub-µm-sized detector N° 3 from the normal conducting to the superconducting state. The zero-resistance critical temperature amounts to T_c = 83.1 K. Current-voltage characteristics recorded at different bath temperatures for the same YBCO detector are depicted in Fig. 3. The critical current at liquid nitrogen temperature is I_c = 1.0 mA, corresponding to a critical current density of j_c(77 K) = 3.2 MA·cm^{-2}. The correspondent

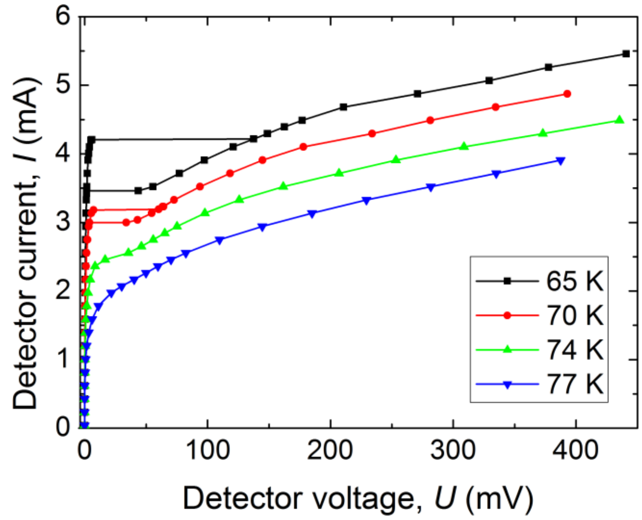

Fig. 3. Current-voltage characteristics of detector N° 3 for different bath temperatures, shown in the legend.

values for all studied detectors can be found in Table I.

III. REAL-TIME MEASUREMENT OF PICOSECOND THZ PULSES

A. Measurement setup

The YBCO detector on the sapphire substrate was glued with its back side to the flat side of an elliptical silicon lens to focus the THz signal onto the planar gold antenna. This hybrid antenna was installed in a detector block inside a cryostat. The copper detector block was connected to the cold plate of the cryostat allowing for the cooling of the superconducting YBCO detector. The cryostat was equipped with a high density polyethylene window that transmits THz radiation and absorbs visible and IR light.

The detector block was developed to shield the detector from external electric fields and to provide broad-band readout with a bandwidth of 30 GHz. A room-temperature bias-tee with a bandwidth of 65 GHz was used to feed the detector with a dc-bias current and to read out the rf signal from the detector. Broad-band flexible cables with a bandwidth of 65 GHz were used as connectors in the readout path that was connected to a real-time oscilloscope providing a bandwidth of either 63 GHz (Agilent DSA-X 96204Q) or 32 GHz (Agilent DSA-X 93204A). According to [5] the effective bandwidth of the readout path can be determined and amounts to $f_{eff} \approx 23.3$ GHz for measurements with the 63 GHz oscilloscope. That corresponds to a temporal resolution of 15.0 ps FWHM and 6.4 ps rms, respectively.

B. Single-shot resolution of the CSR pulse shape at ANKA

At ANKA, a synchrotron source located at the KIT in Germany, CSR is generated in the low-α_c mode where the bunch length is reduced by the use of dedicated optics. Typical bunch lengths are in the range of 15 to 25 ps (FWHM) and can thus be resolved by the aforementioned readout electronics [18],[19]. The experimental setup for the detection of CSR pulses at ANKA by a YBCO detector is depicted in Fig. 4. The THz signal was focused via a parabolic mirror and then split in two equal parts. Two YBCO detectors listed as detector N° 1 and N° 2 in Table I were fed with the THz signal. Detector N° 2 was kept at a constant bath temperature

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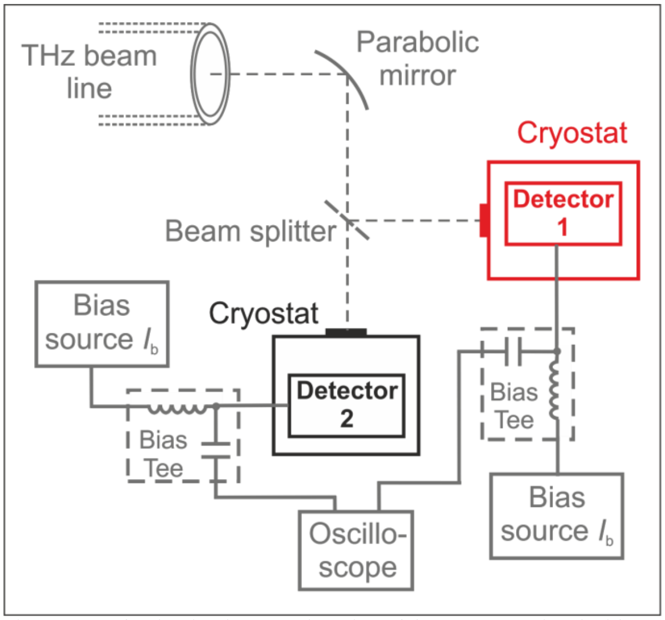

Fig. 4. Setup for the simultaneous detection of the same THz signal with two YBCO detectors.

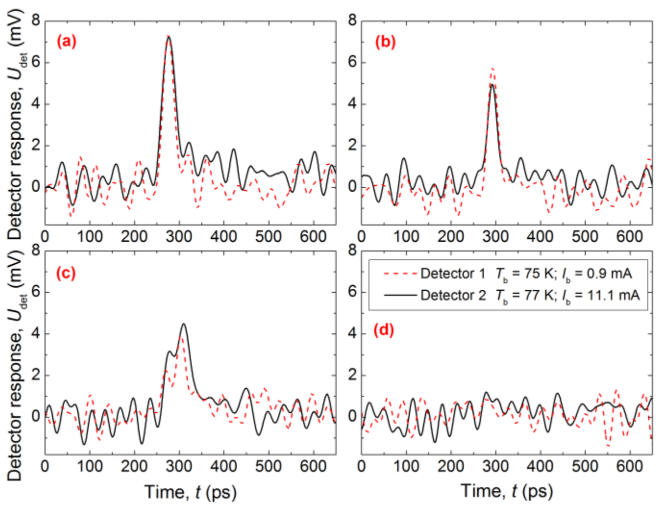

Fig. 5. Bursting THz pulses at the ANKA storage ring recorded in single-shot mode with a sub-µm-sized (detector N° 1) and a µm-sized (detector N° 2) YBCO detector.

of $T_b = 77$ K and biased with $I_b = 11.1$ mA. Detector N° 1 was maintained at $T_b = 75$ K. The bias current required by this sub-µm-sized detector to adjust it to the same signal height as detector N° 2 was much smaller ($I_b = 0.9$ mA). For a thorough investigation of the YBCO-detector response a comparison to another direct THz detector type that is able to resolve the CSR pulse shape would be favorable. Due to the lack of such detectors we compare the signal of two YBCO detectors with different detector volume and operation point. An agreement between predicted electron-bunch lengths at ANKA and averaged pulse widths measured with a µm-sized YBCO detector has already been demonstrated [11].

A single electron bunch was filled in the storage ring. In Fig. 5 the recorded single-shot signal for both detectors is shown. Figs. 5(a)–(d) display the detector signals for several turns of the same electron bunch inside the storage ring. The amplitudes and shapes of the detector response are in each

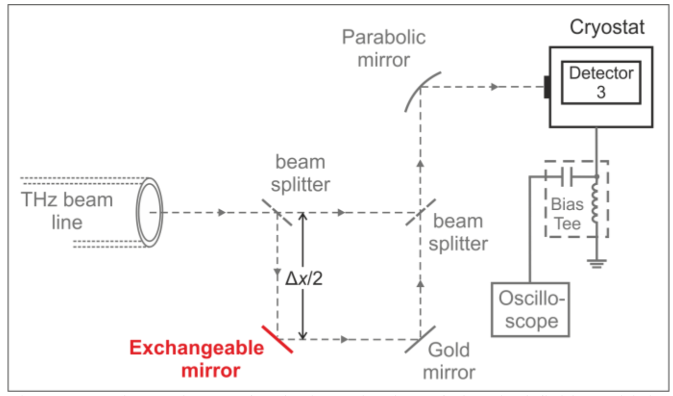

Fig. 6. Experimental setup for the investigation of electrical field sensitivity at ANKA.

case equivalent. From this measurement we conclude that a YBCO detector can follow the shape of a CSR THz pulse with a duration of a few picoseconds independently of the detector's geometry and its operation point. These results indicate an intrinsic response time of the detector that is smaller than the observed pulse widths.

While shape and amplitude of the response of the two YBCO detectors are almost identical for each individual turn of the electron bunch, they differ from turn to turn (See Figs. 5(a)–(d)). This reveals the well-known bursting behaviour of electron bunches in synchrotrons [20]. Therein electrons inside the bunch interact with each other and generate spontaneous bursts of THz radiation. The bursting THz radiation changes the spectral and temporal characteristics of the THz pulse from turn to turn. Due to this effect only single-shot measurements can be used to investigate the properties of the YBCO detector.

IV. Switching of the Direction of the Electrical Field

A. *Measurement setup*

The electrical field sensitivity of a YBCO detector (detector N° 3) was investigated with the setup depicted in Fig. 6. The THz signal was again split in two optical paths and recombined at the second beam splitter. Subsequently it was focused onto the silicon lens of the YBCO detector. The second beam path contained two gold mirrors. One of them is exchangeable against a dielectric $SrTiO_3$ mirror. Electromagnetic waves when reflected at a dielectric material experience a phase shift of π. For the picosecond-scaled CSR pulses this corresponds to a reversal of the direction of the electrical field. On the second beam path the THz signal was shifted by about 700 ps compared to the THz pulse propagating on the first beam path due to the additional length distance of $\Delta x \approx 21.0$ cm. Thus, the setup generated two individual THz pulses irradiating the same sub-µm-sized YBCO detector with a time delay of 700 ps. By exchanging the gold mirror against the $SrTiO_3$ substrate a relative switching of the direction of the electrical field of the second THz pulse was achieved.

The dc input of the bias-tee was terminated with a short. The detector was thus operated at zero bias conditions. Detection of THz radiation with sub-µm-sized YBCO

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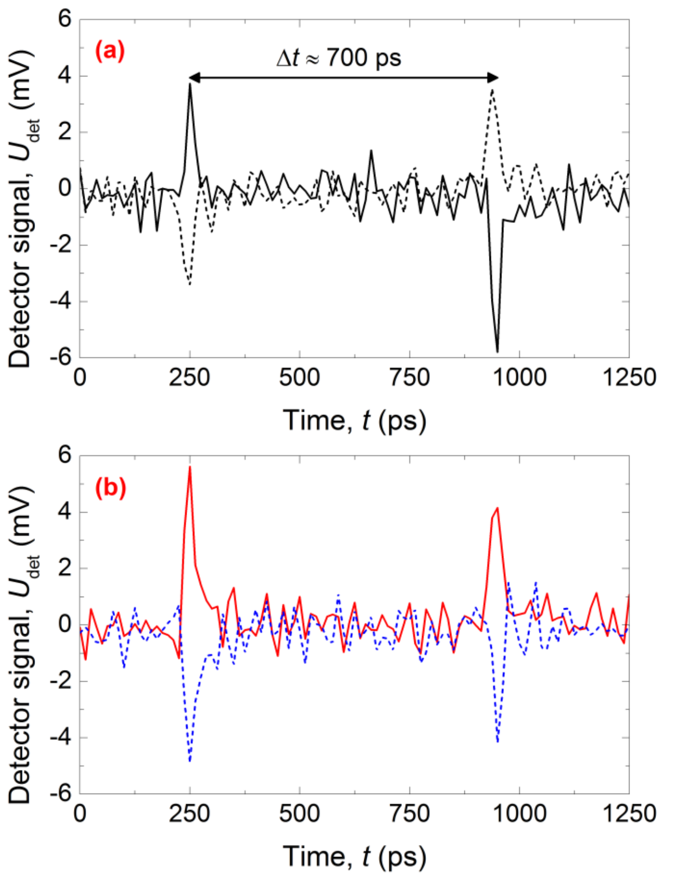

Fig. 7. (a) Two signal traces (depicted by the continuous and the dashed line) measured with detector N° 3 and the gold mirror in the second beam path. (b) Same measurement after switching to the $SrTiO_3$ mirror.

detectors without any applied bias current has been demonstrated [17].

B. Experimental results

Fig. 7(a) shows two exemplary 1250 ps long traces measured with the gold mirror installed in the second beam path. The detector was maintained at a bath temperature close to the critical temperature listed in Table I (T_b = 82.0 K). As expected, the detector signal consists of two pulses with a temporal spacing of approximately 700 ps. The polarity of the two pulses is reversed independently on the polarity of the first pulse. When switching to the dielectric mirror the opposite behavior is observed: a positive pulse is followed by a second positive one and a negative pulse entails a negative one (Fig. 7(b)). This is evidence for the YBCO detector's capability to respond to the direction of the electrical field at operation points near T_c.

Qualitatively the obtained sensitivity of the YBCO detector to the direction of the electrical field for pulsed-THz excitations can be explained in the frame of the model based on dynamics of self-generated vortices [8], [9]. However, so far there is no clear microscopic theory which is able to describe the response of YBCO to THz excitations in all details. At temperatures far from absolute zero, excitations of quasiparticles by rf currents generated from absorbed THz photons cannot be fully excluded. Therefore the exact

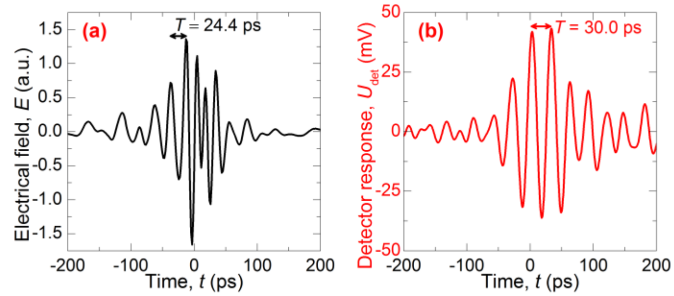

Fig. 8. (a) Simulated electrical field of spontaneous CSR at UVSOR-III. (b) Corresponding measured YBCO detector signal (detector N° 4).

understanding of the processes taking place in YBCO under irradiation with pulsed-THz radiation requires further extensive theoretical and experimental investigations. This requirement is strongly stimulated by real applications of the electrical field sensitivity of the YBCO detectors, one of which will be presented below.

V. Study of the Microbunching at UVSOR-III

The UVSOR-III storage ring is operated at the Institute for Molecular Science in Japan [21], [22]. Several hundred picoseconds long electron bunches spontaneously emit CSR due to the apparition of microstructures when a certain number of electrons inside the bunch is exceeded [23]. The simulation of the emitted electrical field at the point of emission inside the storage ring is depicted in Fig. 8(a). The signal oscillates with a period of T = 24.4 ps. An oscillation of the electrical field on this time scale can be resolved with the described broadband readout electronics by a detector which is sensitive to the direction of the electrical field.

The corresponding measurement with the YBCO detector N° 4 operated at liquid nitrogen temperature and zero-bias conditions is shown in Fig. 8(b). The shape of the recorded signal matches the expected curve. The measured period of T = 30.0 ps differs slightly from the simulated value. This could be due to dispersion of the THz signal while propagating through the storage ring and the THz beamline.

The direct detection of the electrical field of CSR enables the observation of the spatio-temporal evolution of the microbunch structures in the electron bunch circulating in the synchrotron storage ring [24]. So far the YBCO detector is the only direct THz detector for which electrical field sensitivity has been demonstrated.

VI. Conclusion

We have shown that direct THz detectors based on YBCO are able to follow the pulse shape of CSR pulses at the ANKA storage ring independently on the detector's volume and operation point. The intrinsic response time thus amounts to less than 15 ps (FWHM). Single-shot measurements of two consecutive picosecond THz pulses during zero-bias operation demonstrated that the sensitivity of the YBCO detectors depends on the direction of the electrical field. This property allows for the direct analysis of the electrical field emitted in the THz frequency range by substructures in the electron

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bunches at UVSOR-III.

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