

ELECTRICAL FIELD SENSITIVE HIGH- T_C YBCO DETECTOR FOR REAL-TIME OBSERVATION OF CSR*

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Abstract

High- T_C thin-film $\text{YBa}_2\text{Cu}_3\text{O}_{7-x}$ (YBCO) detectors were deployed for the real-time observation of Coherent Synchrotron Radiation (CSR). Due to enhanced fabrication techniques enabling the patterning of sub- μm sized detector areas responsivity values as high as 1V/pJ for pulsed THz excitations have been achieved at the ANKA synchrotron facility at the Karlsruhe Institute of Technology (KIT). Response of the detectors is linear over the whole dynamic range of the IR1 beamline. Combining the picosecond scaled response mechanism of the high-temperature superconductor $\text{YBa}_2\text{Cu}_3\text{O}_{7-x}$ (YBCO) to THz excitations with broad-band readout a temporal resolution of 15 ps full width at half maximum (FWHM) was reached. Real-time resolution of CSR single shots was observed at ANKA and UVSOR-III, the synchrotron facility of the Institute of Molecular Science in Okazaki, Japan.

INTRODUCTION

Storage rings and linear accelerators emitting Coherent Synchrotron Radiation (CSR) supply ultra-short THz pulses of very high brilliance. Pulse durations are in the range of a few picoseconds root mean square (rms) at synchrotrons and even below 1 ps for linac-based THz sources [1], [2]. The single shot study of the CSR bunch shape and its turn-by-turn evolution is a powerful tool for the understanding of electron-electron and wakefield interactions and thus the basis for a further optimization of CSR towards future applications. Therefore real-time resolution of the coherent THz pulses is required.

Most of the existing direct THz detection concepts like semiconducting bolometers or pyroelectric detectors lack of temporal resolution [3], [4]. With a hot-electron bolometer based on the superconductor NbN it was first possible to resolve single bunches in a multi-bunch

environment at the ANKA storage ring [5]. However, the response time of those detectors is limited to approximately 50 ps full width at half maximum (FWHM), and thus the resolution of the actual pulse shape is not possible [6]. More recent developments also indicate room-temperature Schottky barrier diode detectors to be an appropriate choice for the monitoring of CSR pulses [7]. However, response time is so far limited by readout to approximately 200 ps FWHM.

Ultra-fast THz detectors based on the high-temperature superconductor YBCO however do not only meet the requirements for temporal resolution. Short intrinsic response times of less than 2 ps brought up the idea of the YBCO detector for CSR in the first place [8]. The combination of these ultra-fast relaxation processes with broad-band readout give rise to response times of the whole detection system of 15 ps FWHM [9]. Moreover, in contrast to all other existing direct THz detector technologies, the YBCO detector follows the evolution of the electrical field of CSR and not its intensity [10]. Thus the information on the CSR amplitude is preserved just like the phase evolution. This makes the YBCO detector a unique tool for the turn-by-turn observation of CSR.

Here we report on the detector performance depending on the size of the active detecting element in regard to detector responsivity to pulsed THz excitations and the detector's dynamic range. The last part of the report focuses on real-time resolution of the electrical field of CSR at ANKA und UVSOR-III.

YBCO DETECTORS

Detector Fabrication

YBCO thin-films were deposited on both-side polished *R*-plane sapphire. Due to the low dielectric losses of this substrate ($\epsilon_r = 10.06$, $\tan\delta = 8.4 \cdot 10^{-6}$ at 77 K) a back-side illumination of the YBCO detectors is feasible [11]. For the epitaxial growth of the thin-films by a pulsed laser deposition the substrate is kept at a high temperature of

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800° C during deposition. Additional $\text{PrBa}_2\text{Cu}_3\text{O}_{7-x}$ (PBCO) layers below and on top of the 30 nm thick YBCO thin-film were deposited acting as buffer and protection layer, respectively. Furthermore a gold film of 140 nm thickness was deposited in-situ. This procedure allows for good contact resistance between the YBCO/PBCO layers and the gold film needed for the THz antenna and coplanar structures.

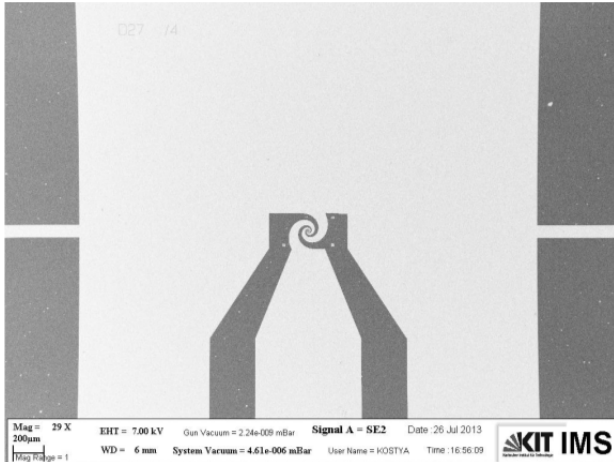


Figure 1: SEM image of the YBCO detector with the planar broad-band THz antenna in the center.

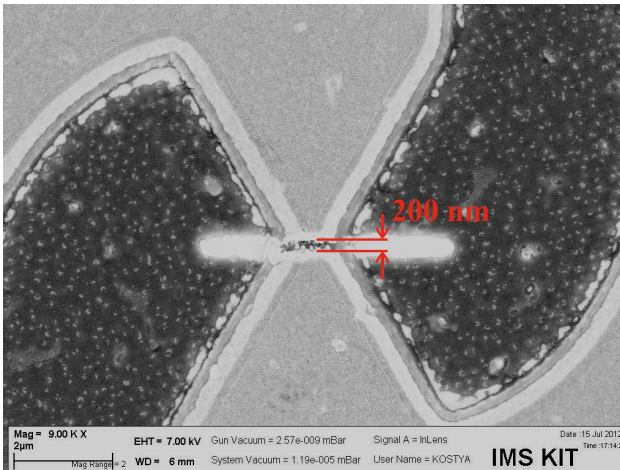


Figure 2: SEM image of a 200 nm long YBCO detecting element embedded in the planar antenna structure. The gold appears in light grey, the substrate is dark grey.

Patterning of the YBCO detector was carried out in two steps. First, the gold covering the area of the detecting element was removed. In this process step the length of the detecting element is defined. Electron-beam lithography, argon ion milling and wet chemical etching with a diluted $\text{I}_2(\text{KI})_5$ solution were used. Optimization of the etching rates and times allowed for almost complete avoidance of underetching of the wet chemical solution and thus for the patterning of detecting elements with lengths of down to 200 nm [12]. Subsequently the definition of the detector width as well as the patterning of the planar broad-band THz antenna and the coplanar

readout lines was carried out. Electron-beam lithography and argon ion milling were applied. Figure 1 shows the YBCO detector with the broadband THz antenna and the coplanar readout. In Fig. 2 a close-up view of the detecting element with 200 nm length and 1.0 μm width in the center of the broad-band THz antenna is displayed.

For the comparison of the detector responsivity depending on the size of the detecting element two YBCO detectors with different volume will be considered subsequently: a smaller detector with an active area of 320 nm in length and 1.3 μm in width and a larger detector measuring 1.9 μm in length and 4.1 μm in width. The YBCO film thickness was in both cases 30 nm.

Detection System

The YBCO detecting element was embedded into a planar log-spiral broad-band THz antenna. The reflection parameter of the antenna for a 50 Ω load was simulated and amounts to less than -10 dB for frequencies between 150 GHz and at least 2.5 THz [10]. The antenna was embedded into the coplanar readout and the whole detector chip was glued with its back side to the flat side of an elliptical silicon lens to focus the THz signal onto the antenna. This hybrid antenna construct was installed in a detector block inside a cryostat. The copper detector block was connected to the cold finger of the pulse tube cooler and allowed for the cooling of the superconducting YBCO detector. The operation temperature range was adjustable between 60 and 90 K. The cryostat was equipped with a high density polyethylene window that transmits THz radiation and absorbs visible and IR light.

Furthermore the detector block was developed to shield the detector from external electric fields and to provide a readout of the detector with a large bandwidth of 30 GHz. The connection to the room-temperature bias-tee with a bandwidth of 65 GHz was realized with broad-band flexible cables (65 GHz bandwidth) as well as the connection to the real-time oscilloscope providing a bandwidth of 63 GHz (Agilent DSA-X 96204Q). The effective bandwidth of the described readout path was determined according to [13] and amounts to $f_{\text{eff}} \approx 23.3$ GHz. That corresponds to a minimal readout pulse width of 15.0 ps FWHM and 6.4 ps rms respectively.

DETECTOR PERFORMANCE AT ANKA

The responsivity and the dynamic range of different YBCO detectors were investigated at ANKA. The ring was operated at a beam energy of 1.3 GeV in low-alpha multi bunch mode. Measurements were performed at the IR1 beamline. The total THz power emitted at the beamline was determined by the use of a calibrated photo-acoustic THz powermeter [14]. The average energy that was coupled to the YBCO detector was estimated via the coupling efficiency as in [10]. For the aforementioned YBCO detectors the coupling efficiency amounted to $\eta = 3.82\%$ and $\eta = 3.76\%$ for the small and the large YBCO detector respectively where the small coupling

efficiencies are due to the impedance mismatch between the broad-band THz antenna ($Z_a = 60 \Omega$) and the impedance of the detecting element ($Z_d = 320 \Omega$ and $Z_d = 290 \Omega$ for the smaller and the larger detector respectively).

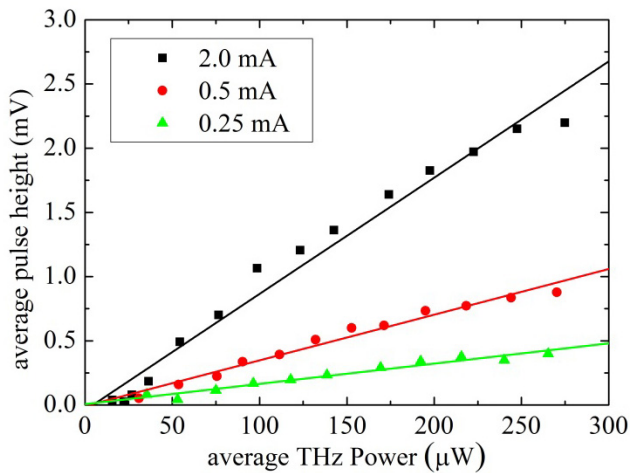


Figure 3: Dynamic range of the larger YBCO detector at a bath temperature of $T_b = 77$ K and different bias currents.

Figure 3 shows the dependence of the average pulse height measured with the aforementioned larger YBCO detector at a bath temperature of $T_b = 77$ K and a 32 GHz real-time oscilloscope on the emitted THz power. For different bias conditions the detector shows linear behaviour over the whole dynamic range of the IR1 beamline. The noise limit of the THz powermeter was around 15 µW.

The patterning of thin-films to sub-µm sized structures provides high responsivities and allows for the detection of small CSR powers. The determination of the intrinsic detector responsivity via the coupling efficiency and the averaged measured pulse height yields a maximum value of 160 mV/pJ for the larger YBCO detector. The sub-µm sized smaller detector shows responsivities of 1.06 V/pJ for optimal operation conditions. These results are comparable to previous measurements [8].

REAL-TIME MEASUREMENTS

During multi bunch operation at ANKA individual bunches are separated by 2 ns [1]. With a response time of the YBCO detection system of 15 ps FWHM single bunches can be resolved in a train of several electron bunches [8]. Figure 4 shows the pulse shape of a typical single CSR pulse recorded with a sub-µm sized YBCO detector. The pulse width amounts to 6.7 ps rms corresponding to 15.7 ps FWHM. Due to the high detector responsivity the signal was recorded in Zero bias operation mode [10]. According to the operation conditions of ANKA during this measurement the recorded average pulse width of 9.3 ps rms could be accounted to the actual bunch length [9].

At UVSOR-III CSR is emitted spontaneously due to microbunching instabilities that appear when a certain

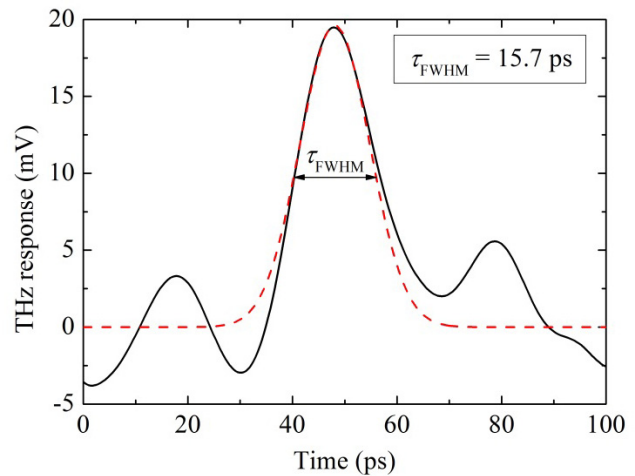


Figure 4: Real-time resolution of a single CSR pulse at the ANKA storage ring.

number of electrons inside the bunch is exceeded [15]. The emitted CSR signal consists of an oscillation of the electrical field around the zero level on a rather long time scale of 30.5 ps which can be resolved with the broad-band readout electronics. The ability of the YBCO detector to display this oscillating signal points out the sensitivity to the electrical field.

CONCLUSION

A detection system based on direct YBCO THz detectors with ps readout times has been developed and characterized in terms of sensitivity and dynamic range. Responsivities of more than 1V/pJ were found for sub-µm sized YBCO detectors.

Real-time resolution of single CSR pulses was demonstrated at ANKA and the UVSOR-III storage ring. Furthermore, the YBCO detector has shown to be sensitive to the electrical field of THz radiation. Thus ultra-fast YBCO detectors embedded in high-frequency readout are a promising candidate for the observation of the electric field of CSR pulses.

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