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$YBa_2Cu_3O_{7-\delta}$ quasioptical detectors for fast time-domain analysis of terahertz synchrotron radiation

P. Probst,[1,a)] A. Scheuring,[1] M. Hofherr,[1] D. Rall,[1] S. Wünsch,[1] K. Il'in,[1] M. Siegel,[1] A. Semenov,[2] A. Pohl,[3] H.-W. Hübers,[2,3] V. Judin,[4] A.-S. Müller,[4] A. Hoehl,[5] R. Müller,[5] and G. Ulm[5]

[1]*Institute of Micro- and Nanoelectronic Systems, Karlsruhe Institute of Technology, Hertzstrasse 16, 76187 Karlsruhe, Germany*
[2]*Institute of Planetary Research, DLR e.V., Rutherfordstrasse 2, 12489 Berlin-Adlershof, Germany*
[3]*Institute of Optics and Atomic Physics, Technical University of Berlin, 10623 Berlin, Germany*
[4]*Laboratory for Applications of Synchrotron Radiation, Karlsruhe Institute of Technology, Engesser Strasse 15, 76131 Karlsruhe, Germany*
[5]*Physikalisch-Technische Bundesanstalt (PTB), Abbestrasse 2-12, 10587 Berlin, Germany*

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Thin $YBa_2Cu_3O_{7-\delta}$ (YBCO) film detectors embedded into a log-spiral planar antenna were implemented for the detection and analysis of ultrashort terahertz pulses emitted by electron bunches in a synchrotron storage ring. In the direct detection mode terahertz radiation pulses from single electron bunches were resolved. A response time of 45 ps was determined as the full width at half maximum of the voltage transient at the output of the detection system. The sensitivity of the YBCO detector to pulsed terahertz radiation was 70 mV/pJ along with a sensitivity of 30 V/W for continuous radiation at 0.8 THz and a very broad dynamic range of over 30 dB. We found experimental evidences of a nonbolometric nature of the detection mechanism. © *2011 American Institute of Physics*. [doi:10.1063/1.3546173]

Transverse acceleration of relativistic electrons in storage rings when they pass deflecting magnets leads to the emission of synchrotron radiation in the form of short pulses. The electrons in a storage ring do not form a continuous stream but are grouped in bunches. This is a direct consequence of the radio frequency (rf) system used to transfer power to the electrons. Coherent synchrotron radiation (CSR) from an electron bunch is emitted at a particular wavelength λ_0 when the bunch length is reduced below this wavelength. The total power emitted by N_e electrons in a bunch can be presented as $P_{total}=N_e P_e(1+N_e \cdot f_\lambda)$ (Refs. 1 and 2), where P_e is the power emitted by a single electron and f_λ is a form factor that is given by the length and shape of the bunch. If the bunch length is reduced below the wavelength λ_0, the second part of the equation becomes dominant and the emitted power increases drastically. For non-CSR, typical pulse durations range between 30 and 100 ps (Ref. 3). Short electron bunches and, consequently, short CSR pulses with durations down to 1 ps are achieved at electron storage rings operating in the low-alpha mode.[3] Analysis of these very short pulses requires ultrafast terahertz detectors.

There already exists a variety of direct terahertz detectors. There are room-temperature detectors like Schottky diodes,[4] conventional bolometers,[5] microbolometers,[6] and Golay cells, which are often limited in application due to low sensitivity and/or long response times. Cooled detectors are often preferred to achieve higher sensitivity. The most common commercial systems are helium-cooled composite bolometers with a noise equivalent power (NEP) of about 10^{-13} W/$\sqrt{\text{Hz}}$ at 4 K (Ref. 7). However, they typically have rather large response times of a few microseconds. Experiments on the photoresponse of superconductors in the past showed that superconducting detectors are promising candidates for fast direct detection.[8] The detection of terahertz CSR at different synchrotron facilities with a NbN superconducting hot-electron bolometer (HEB) was already demonstrated.[9–11] Another prospective material is the high-temperature superconductor $YBa_2Cu_3O_{7-\delta}$ (YBCO). Due to its very fast photoresponse to pulsed radiation in the optical and infrared spectral range,[12–15] it may provide even smaller response times. By means of the electro-optical sampling technique, the fast-relaxation time of the YBCO optical response was found to be about 1 ps (Ref. 12). One has to mention that the complete relaxation of the optical response lasts much longer; the slow-relaxation time mostly depends on the phonon escape from the film to the substrate. The corresponding characteristic time τ_{es} is proportional to the thickness of the YBCO film. Typical τ_{es} values are in the nanosecond range.[16,17] By the proper choice of the operation point this slow component can be suppressed allowing the fast-relaxation to entirely define the response time of the detector. The possibility to resolve picosecond terahertz CSR pulses makes it feasible to study not only beam dynamic effects in the single-bunch mode but also possible influences on the terahertz emission of the single bunch in the multibunch environment. This explains the recently emerged demand of the synchrotron community for ultrafast terahertz detectors.

In this letter, we report the development of a superconducting YBCO terahertz detection system having the potential of picosecond time-domain analysis of terahertz CSR.

The YBCO thin films were prepared using the pulsed-laser deposition (PLD) technique. To ensure low dielectric losses at terahertz frequencies, the YBCO films were grown on both-side polished *R*-plane sapphire substrates. A CeO_2 buffer layer with a thickness of 8 nm was deposited at a

[a)]Electronic mail: petra.probst@kit.edu.

substrate temperature of 820 °C and an oxygen pressure of p_{O2}=0.9 mbar. The YBCO film with a thickness of about 40 nm was deposited on top of the CeO_2 layer at the same temperature and an oxygen pressure of p_{O2}=0.7 mbar. For the Au deposition the vacuum chamber was evacuated to a pressure of $5 \cdot 10^{-5}$ hPa and a 140 nm Au layer was grown *in situ* using the same PLD technique.

The multilayers were patterned in several steps by electron-beam lithography. The effective YBCO detecting area was opened by etching the Au layer with an I_2-*KI* solution. Ion-milling was used to pattern the coplanar readout line and the Au antenna. The antenna was designed to cover the CSR spectral range (0.1–2 THz) of a typical synchrotron radiation source.[2] The superconducting YBCO detector (5 μm wide, 3 μm long) had a normal state resistance before the transition of about 55 Ω in agreement with the 90 Ω square resistance of nonpatterned YBCO films. With a negligible spread, all detectors had the same critical temperature (T_c=86 K) as the freshly deposited films and a critical current density of j_c=2 MA/cm^2 at 77 K which is in good agreement with already published values.[18] The fabricated detectors were characterized with a continuous wave (CW) source at 0.8 THz. The responsivity and NEP were found to amount to 30 V/W and $9.8 \cdot 10^{-8}$ W/$\sqrt{\text{Hz}}$, respectively. The detectors were glued to the rear side of an elliptical silicon lens and mounted in a detector block, which was thermally anchored to the cold-plate in the vacuum chamber of a liquid nitrogen bath cryostat with optical access.

The response of the detectors to CSR was measured with two different readout configurations. Real-time measurements on the microsecond time-scale required enlarged sensitivity that prohibited the use of the full readout bandwidth, especially its low frequency part. Hence, a detector holder with an integrated bias-tee and amplifiers with only 4 GHz bandwidth were used before feeding the output signal to a real-time oscilloscope. The overall readout bandwidth resulted in about 3 GHz. Although in this case the time resolution of the detection system was limited by the readout electronics, it was sufficient for distinguishing CSR pulses from neighboring electron bunches separated by 2 ns as well as to record in real time the CSR from a few sequential revolutions of electron bunches. In another configuration, to achieve an ultimate response time and preserve the intrinsic shape of the voltage transient of the detector, the bias supply was realized via a room-temperature bias-tee with a bandwidth of 25 GHz. Furthermore, the amplifier bandwidth was increased to 18 GHz and the real-time oscilloscope was replaced by a sampling oscilloscope with a bandwidth of 20 GHz.

The experiments were performed at two synchrotron facilities. One is ANKA,[19] the synchrotron light source of the Karlsruhe Institute of Technology, which can accommodate up to 184 bunches. The distance between two adjacent bunches is 2 ns corresponding to the 500 MHz frequency of the rf system. The typical filling pattern of the ANKA storage ring consists of three trains separated by a 20 ns gap. Each train consists of about 34 bunches. The other is the Metrology Light Source (MLS) of the Physikalisch-Technische Bundesanstalt. MLS is the first electron storage ring worldwide dedicated for the low-alpha operation mode and hence for the production of high power terahertz CSR.[20,21] The storage ring can accommodate any number of bunches of up to 80 spaced by 2 ns.

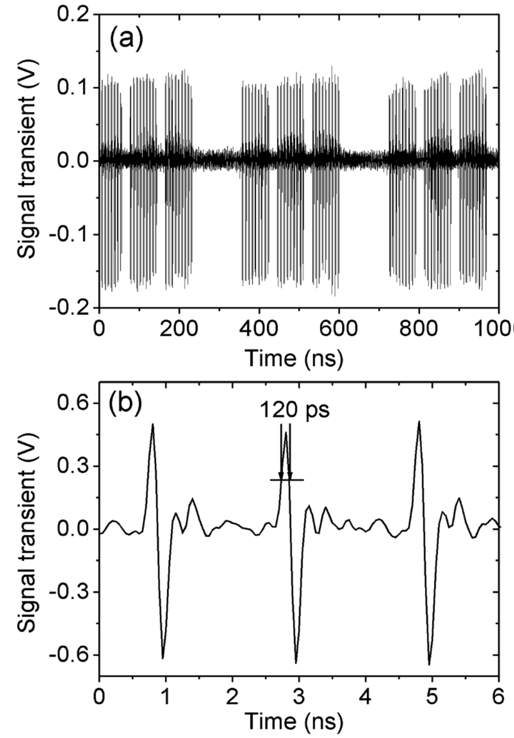

FIG. 1. (a) Standard filling pattern of the ANKA storage ring recorded via CSR with the YBCO detector. The distance between the trains is 20 ns (50 MHz) and the revolution frequency is about 2.7 MHz. (b) Output transient representing three single-bunch radiation pulses.

The output signal transient shown in Fig. 1 was recorded with the standard filling of the ANKA storage ring. The transient [Fig. 1(a)] covers the three consecutive turns of the complete filling pattern. The response to CSR pulses from single bunches are displayed in Fig. 1(b). Due to the integrated bias-tee with reduced bandwidth, a few picoseconds long CSR radiation pulse is presented by the transient with a positive and a negative part. The full width at half maximum (FWHM) of the positive peak was 120 ps that corresponded to the overall readout bandwidth of 3 GHz.

Figure 2 shows the response of the detector with the enlarged readout bandwidth to the radiation of a single bunch. Although the readout lines were still not matched

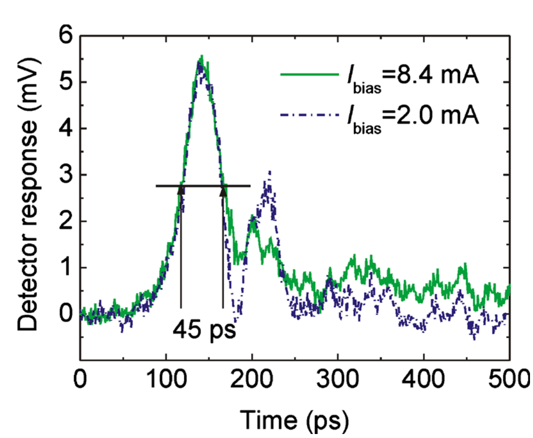

FIG. 2. (Color online) Detector response to single-bunch radiation at MLS for bias currents of 2.0 and 8.4 mA and corresponding dc resistances of 2.5 and 40 Ω.

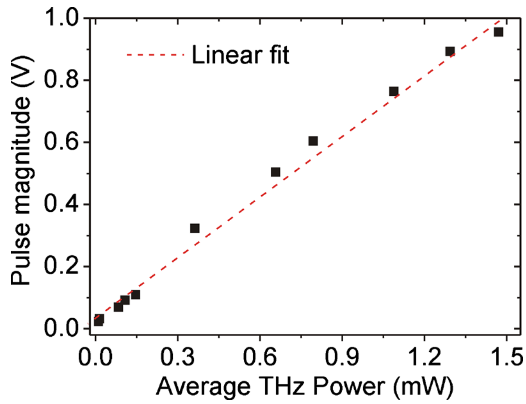

FIG. 3. (Color online) Magnitude of the single pulse in the output signal transient for different average terahertz CSR power. The dashed line is a linear fit to the data.

perfectly, which caused signal reflections and delayed replicas with a repetition time of approximately 75 ps, the FWHM of the main peak dropped to 45 ps. This is a reduction by a factor of four compared to the resolution achieved with the NbN HEB in a setup with a readout bandwidth of 3.5 GHz.[10] We note that the response time and the shape of the output transient of the detector do not practically depend on its dc resistance as long as the detector remains within the superconducting transition (see Fig. 2 where two output transients are displayed for two different operation points).

The dynamic range of the detector was determined by reducing the stored electron current (number of electrons in the bunch) in the storage ring, which causes a corresponding decrease of the CSR power. The operating point providing maximum sensitivity was in the resistive transition where the dc resistance and the differential resistance of the detector were 20 and 50 Ω, correspondingly. The dependence of the pulse magnitude in response to single-bunch radiation on the average terahertz power is displayed in Fig. 3. The saturation level of the amplifier was above 1 V. Over the whole measurable terahertz power range from about 1 to 1500 μW the detector response was proportional to the terahertz power, hence pointing out the dynamic range of the YBCO detector in excess of 30 dB. Earlier published results[10] demonstrated the saturation of the NbN HEB in a similar operation regime limiting the dynamic range to less than 15 dB. Taking into account the amplifier gain and the estimated optical coupling to the YBCO detector we arrived at a detector sensitivity of 68 mV per 1 pJ per pulse. The direct comparison with the sensitivity to CW radiation is not possible without knowing the exact pulse duration of the terahertz CSR.

We have to note here that the response of our YBCO detectors to visible light pulses differed considerably from that to the CSR. We compared the voltage transients reported in this letter with detector signals obtained with 26 fs long radiation pulses from a $TiAl_2O_3$ laser at a wavelength of 0.8 μm while preserving in both cases the same pulse energy density and operating the detector at the same temperature and bias current. The detector response to visible light showed tiny fast features on top of a dominating slow relaxation and was strongly nonlinear with both the bias current and the pulse energy. This observation plausibly evidences an earlier reported[14] nonbolometric nature of the detection mechanism in the terahertz frequency regime.

We have developed the fabrication process for superconducting YBCO thin film detectors operating above 77 K. The detectors were tested at two different synchrotron terahertz sources. The filling pattern as well as terahertz CSR of a single electron bunch was successfully resolved by the detectors. The FWHM of the detector response to CSR pulses of a single electron bunch was reduced to about 45 ps. We expect that further extension of the readout bandwidth will allow us to achieve a temporal resolution better than 20 ps, thus approaching the natural duration of CSR pulses.

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