SINGLE-SHOT THz SPECTROSCOPY FOR THE CHARACTERIZATION OF SINGLE-BUNCH BURSTING CSR

J. Raasch[†], M. Arndt, K. Ilin, A. Kuzmin, A. Schmid, M. Siegel, S. Wuensch, Institute of Micro- and Nanoelectronic Systems, Karlsruhe Institute of Technology (KIT), Karlsruhe, Germany
A.-S. Mueller, J. L. Steinmann,
Laboratory for Applications of Synchrotron Radiation, KIT, Karlsruhe, Germany
G. Cinque, M. D. Frogley, Diamond Light Source, Didcot, United Kingdom
J. Hänisch, B. Holzapfel, Institute for Technical Physics, KIT, Karlsruhe, Germany

Abstract

An integrated array of narrow-band high-T_c $YBa_2Cu_3O_{7-x}$ (YBCO) detectors embedded in broad-band readout was developed for the future use at synchrotron light sources as a single-shot terahertz (THz) spectrometer. The detection system consists of up to four thin-film YBCO nanobridges fed by planar double-slit antennas covering the frequency range from 140 GHz up to 1 THz. We present first results obtained at the ANKA storage ring and at Diamond Light Source during operation of two and four frequency-selective YBCO detectors, respectively.

INTRODUCTION

Brilliant Coherent Synchrotron Radiation (CSR) from short, relativistic electron bunches opens a broad range of applications, amongst them terahertz (THz) imaging and spectroscopy. One prominent way to generate CSR is the use of dedicated low-alpha optics in an electron storage ring [1]. Herein, the bunch length is reduced to sub-mm dimensions leading to the coherent emission at wavelengths longer than the overall bunch length, thus in the THz frequency range. The low-alpha mode, however, entails electron beam instabilities, the so-called micro-bunching, once the beam current exceeds a certain threshold [2]. This leads to a variation in the temporal and spectral shape of the emitted THz radiation pulses. The micro-bunching is characterized by the occurrence of bursts of THz radiation at wavelengths shorter than the overall bunch length. These instabilities restrain the possible range of usage of CSR. Moreover, the micro-bunching instabilities limit the possible bunch compression and thus the level of emitted THz radiation power. Optimization of the emitted CSR requires a deeper understanding of the micro-bunching mechanisms. To this end, single-shot and turn-by-turn resolution of the THz signal is needed.

The short pulse lengths during low-alpha operation (ps/sub-ps) combined with high revolution frequencies (above 100 kHz) prevents the use of most room-temperature and liquid helium cooled semiconductor THz detectors. Response times of commercial pyroelectric sensors and semiconducting bolometers are limited at around tens of milliseconds and several hundred nanoseconds, respectively [3]. As compared to that, the characteristic times during the measurements at ANKA are 15 – 20 ps full width at half maximum (FWHM) for the pulse lengths and 2 ns between two consecutive pulses, corresponding to 500 MHz repetition rate [4]. At Diamond Light Source the characteristic pulse length was about 8 ps FWHM, the repetition frequency is the same as at ANKA [5]. Superconducting detectors offer both a high sensitivity and fast response times. First bunch-by-bunch resolution of CSR pulses was demonstrated by the use of superconducting NbN hot-electron bolometers with response times of 165 ps FWHM by Semenov et al. [6]. However, the resolution of the single pulse's temporal shape is not viable with those detectors.

Highest temporal resolution in direct detection is offered by detectors based on the high-T_c material $YBa_2Cu_3O_{7-x}$ (YBCO). Response times as fast as 16 ps FWHM have been demonstrated [7]. Here the limiting factor was identified to be the readout electronics rather than intrinsic response times of YBCO that lie in the range of 1 – 2 ps only [8]. Moreover YBCO THz detectors offer zero bias detection combined with the unique feature of electrical field sensitivity, both of them being based on the intrinsic detection mechanism for direct THz irradiation [9, 10].

At ANKA the overall bunch length of individual CSR pulses could be observed using the YBCO detection system [7]. The substructure on the bunch that arises during bursting can however not be resolved with state-of-the-art electronics. Therefore single-shot THz spectroscopy is a promising new candidate to gain further insight into the bunch profile. For that, single-shot spectral resolution needs to be combined with the ability to resolve individual bunches in a multi-bunch environment. By transforming the information from the single-shot spectra to the time domain, even shorter bunch lengths and substructures can be observed.

Due to its fast intrinsic relaxation processes YBCO was selected as detector material and embedded into narrow-band antennas combined with broad-band readout, as described in the next section. The second part of this report focuses on first tests of planar double-slot antennas under pulsed irradiation that have been conducted at the ANKA storage ring. The narrow-band operation of an array consisting of four detectors has been demonstrated

This work was supported by the German Federal Ministry of Education and Research (Grant 05K13VK4), by the Helmholtz International Research School for Teratronics and the Karlsruhe School of Elementary Particle and Astroparticle Physics: Science and Technology.
[†] juliane.raasch@kit.edu

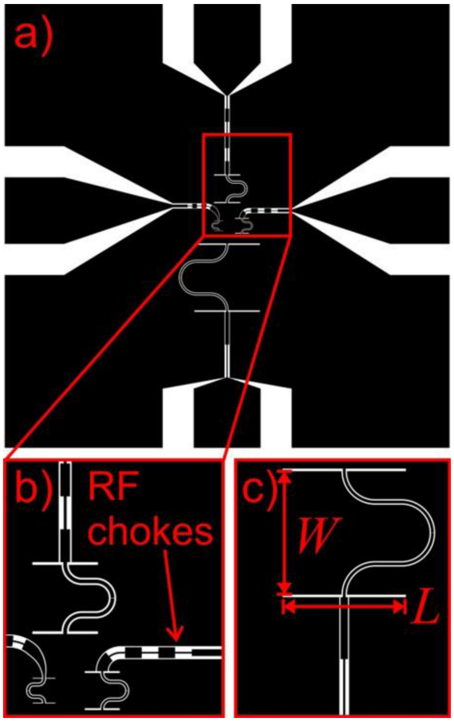

Figure 1: (a) Four-detector array with close-up view of the RF chokes (b) and the high impedance antenna design (c). The gold metallization is depicted in black and white areas correspond to the bare sapphire substrate.

recently at the MIRIAM beamline B22 at Diamond Light Source.

YBCO DETECTION SYSTEM

Antenna Design

The frequency-selective coupling of radiation to the YBCO detecting element is realized with planar double-slot antennas which were designed for center frequencies of 140 GHz, 350 GHz, 650 GHz and 1.02 THz. Figure 1a shows the array design of the 3 mm × 3 mm detector chip. Simulations of the antennas were performed with CST Microwave Studio [11]. Recently a good coupling efficiency and narrow-band behaviour were demonstrated for double-slot antennas combined with a YBCO detecting element [12].

To cope with the demand for excellent matching between the antenna and the YBCO detector impedance, the antenna layout has been adapted for higher impedances as can be seen in Fig. 1c. Therefore, the slot length L was set to $\lambda/2$ to achieve high slot impedance. The coplanar waveguide between slot and detector also has a length of $\lambda/2$ to retain the impedance at the position of the detecting element. The curving of the waveguide with the off-centred detecting element ensures an optimum distance W between the two slots. An additional benefit of the long waveguide is the improved narrow-band behaviour of the antenna. Antenna impedances as high as 300 Ω to 350 Ω are provided by this design. For a detector impedance

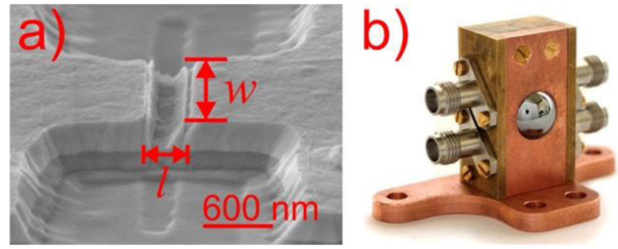

Figure 2: (a) SEM image of readily processed YBCO detecting element with typical lateral dimensions of $l = 180$ nm and $w = 1500$ nm. The 200 nm thick gold metallization layer can be distinguished from the underlying ceramic layers (CeO_2, PBCO and YBCO). (b) 4-channel detector block with silicon lens.

with a real part of 350 Ω the simulations predict antenna bandwidths of approximately 7% for all four antennas.

Isolation between the detector and the readout path at the antenna frequency is obtained through RF-chokes, see Fig. 1b. The distance between the individual antennas of the array was chosen to minimize detector crosstalk while maintaining a high directivity. Further information on the array design process can be found in [12].

Detector Fabrication

For the YBCO detectors double-side polished *R*-plane sapphire was used as substrate. This ensures the transmission of THz radiation with low dielectric losses ($\varepsilon_r = 10.06$, $\tan\delta = 8.4\cdot 10^{-6}$ at 77 K), [13]. High-quality YBCO thin films are grown by pulsed laser deposition (PLD). The deposition of 8 nm CeO_2 and 25 nm $PrBa_2Cu_3O_{7-x}$ (PBCO) buffer layers allow for the epitaxial growth of a 25 nm thick YBCO film [14, 15]. The superconducting thin film is sandwiched between the buffer layers and a 25 nm PBCO capping layer acting as protection during patterning. A gold film is deposited atop the multilayer structure to benefit from the lower surface resistance of gold as compared to YBCO at frequencies above 150 GHz [16]. *In-situ* deposition of a 20 nm thin gold film ensures good contact resistances between gold and YBCO. Further 180 nm of gold were deposited *ex-situ* using DC magnetron sputtering. As compared to PLD grown gold films, the sputtered gold films exhibit significantly improved film-thickness homogeneity and guarantee reproducible etching due to the smaller grains.

Patterning of the YBCO detectors was carried out in two steps. At first, the length l of the detecting element was defined by removing the gold in the area of the actual detecting element. The patterning of the resist mask was done by electron-beam lithography (EBL), and gold etching was realized as a combination of argon-ion milling and wet-chemical etching. Herein the ion milling allows for anisotropic etching of the first 180 nm of the slit while the wet-etching solution removes the remaining 20 nm without altering the oxygen content of the underlying ceramic layers. The slit area of the gold removal can be seen as small cavities adjacent on both sides of the detecting element in Fig. 2a. The second step defines the width

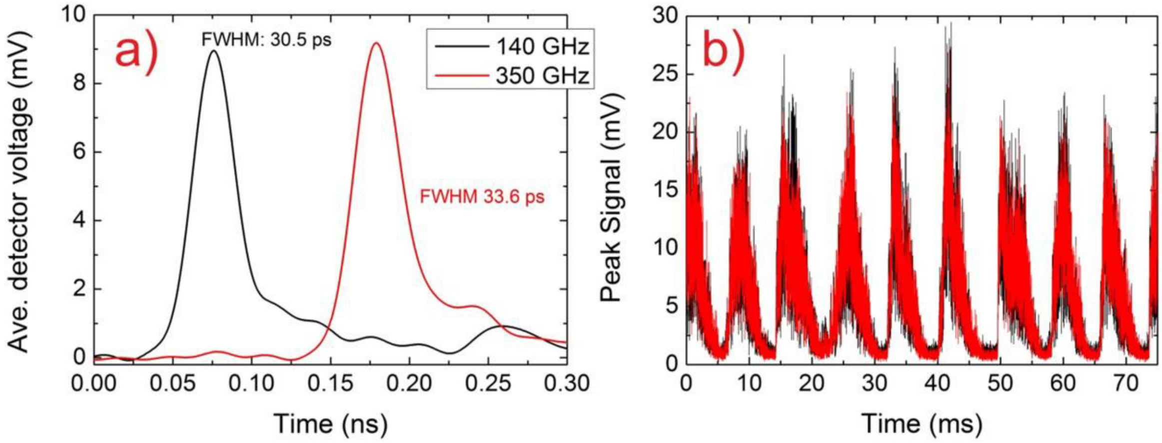

Figure 3: (a) Single-shot detector responses of the 140 GHz and 350 GHz detector. (b) Bursting at 140 GHz and 350 GHz as observed at the IR2 beamline at ANKA.

of the detecting element and the planar narrow-band antennas as well as the coplanar design of the detector chip. To this end, consecutive EBL and argon-ion milling are carried out. Further details on the fabrication process can be found in [17].

The patterning process described above enables the fabrication of superconducting structures with critical temperatures as high as $T_c \approx 84$ K. Intrinsic responsivities to pulsed excitations of up to 1.0 V/pJ have been demonstrated at the ANKA synchrotron [18].

Cryostat Design

Direct readout of the YBCO detector array is done through broad-band connection lines. For that, the sapphire chip is glued to the flat side of a high-resistivity silicon lens, which along with the narrow-band antennas is acting as a hybrid antenna [19]. The back-side illuminated detector is mounted in a four-channel detector block (Fig. 2b) made of copper to ensure good thermal coupling to the cold plate of the liquid nitrogen cryostat used to provide the operation temperature of 77 K. Four V-compatible coaxial readout lines for frequencies up to 65 GHz connect the detector block to four room-temperature broad-band SHF BT65 bias tees. The RF ports of the bias tees are fed to a real-time oscilloscope to read out the signal coming from the detectors, while the DC ports are used for the biasing of the individual YBCO detectors. To this end, the system is equipped with four individual precision current sources.

TWO-CHANNEL MEASUREMENTS AT ANKA

A prototype detection system with two narrow-band detectors operating simultaneously at 140 GHz and 350 GHz was tested at the IR2 beamline of the ANKA storage ring during low-alpha operation at 1.3 GeV. The filling pattern consisted of a single bunch.

The detectors were operated at 80 K bath temperature and biased at their working point of optimal sensitivity. An Agilent DSA-X 93204A real-time oscilloscope with 32 GHz bandwidth was used to read out both detectors simultaneously. No amplifier was employed.

The detector signals recorded during a single CSR pulse are depicted in Fig. 3a. The difference in peak time can be accounted to variations in the length of the readout paths. Both detectors exhibit response times of approximately 30 ps (FWHM) [20]. Here, the limiting factor is the readout bandwidth rather than the detector speed. A simultaneous recording of the bursting at both frequencies can be seen in Fig. 3b.

FOUR-CHANNEL SIMULTANEOUS DETECTION AT DIAMOND

The 4-channel detector array has been examined at the MIRIAM beamline at Diamond Light Source. The synchrotron was operated in low-alpha mode at an energy of 3 GeV and a bunch length of 3.5 ps rms [21]. The beam current amounted to 10 mA and was kept constant by top-up every hour, thus ensuring stable conditions above the bursting threshold. The filling pattern was designed as a hybrid filling consisting of a multi-bunch train of 200 bunches and a single bunch at a distance of 368 buckets. The current in every single bunch corresponded to 50 µA.

A cut-off of about 50% in the frequency range between 300 – 500 GHz has been observed at the experimental endstation posing additional requirements to the YBCO detector sensitivity [22]. Figure 4 shows the single-shot peak signal of all four detectors during two different bursts recorded on a bunch-by-bunch basis. As can be seen, the detector sensitivity is sufficient to detect the bursting CSR in the frequency range of 140 GHz up to 1 THz. In Fig. 4a the low frequencies start to appear first when the bunch compresses whereas the higher frequencies start to burst later. However, in Fig. 4b a different kind of burst can be seen. The burst is less intense but longer in duration. Moreover, initially all four frequencies appear simultaneously (approximately at 39.15 ms) but the higher frequencies decline first.

ISBN 978-3-95450-177-9

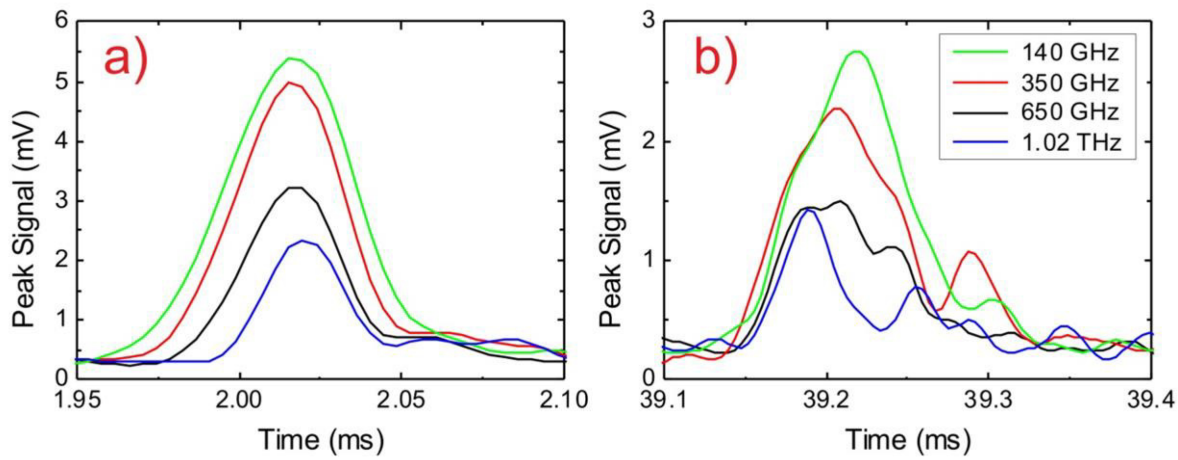

Figure 4: Bursting CSR at Diamond Light Source. Two different burst patterns and their frequency dependence are depicted in (a) and (b).

The frequency-dependent behaviour of the individual detectors was investigated by Fourier-Transform Infrared interferometry and via THz bandpass filters. Both measurement methods show good agreement and for the specific case of the 650 GHz antenna a center frequency between 650 and 700 GHz is observed. The detailed discussion of these results can be found in [23].

CONCLUSION

We have developed a THz detection system that enables the single-shot bunch-by-bunch monitoring of CSR at four distinct frequencies. To this end, a fabrication process aiming for ultimate detector sensitivity has been implemented and custom-made narrow-band antennas have been designed to match the high detector impedance. At two and four frequencies, respectively, the bursting behaviour has been observed at the ANKA storage ring and Diamond Light Source revealing frequency-dependent behaviour of the bursts. From those measurements, the need for single-shot spectroscopic resolution of bursting CSR becomes apparent.

Future development of the single-shot THz spectroscopy system includes calibration to be able to use the existing four-channel setup for characterizing bursting CSR. Extending the range of use to higher frequencies and the evolution of the system to larger pixel numbers will make it available also for the application at linear accelerators. This demands the introduction of new readout concepts as the herein presented direct readout with real-time oscilloscopes is limited to four channels and lacks memory depth. One approach to overcome this limitation has been presented by Caselle et al. in the form of the KAPTURE readout electronics [24].

ACKNOWLEDGEMENT

The authors would like to thank the beamline scientists and technical staff at the infrared beamlines at ANKA for the continuous support. Moreover, we thank Diamond Light Source for access to and extensive assistance at the MIRIAM beamline, B22 (SM 12495), that contributed to the results presented here, as well as for support from the EU.

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ISBN 978-3-95450-177-9