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# THz properties of long $\text{YBa}_2\text{Cu}_3\text{O}_{7-\delta}$ bicrystal Josephson junction studied with a Cold Electron Bolometer

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**Abstract:** The response of the Cold-Electron Bolometers (CEBs), integrated into a 2-D array of dipole antennas, has been measured by irradiation from  $\text{YBa}_2\text{Cu}_3\text{O}_{7-\delta}$  (YBCO) 50  $\mu\text{m}$  long Josephson junction into the THz region at frequencies from 0.1 to 0.8 THz. The possibility of controlling the amplitude-frequency characteristic is demonstrated by the external magnetic field in the traveling wave regime of a long Josephson junction. YBCO junction has been formed on the bicrystal  $\text{Zr}_{1-x}\text{Y}_x\text{O}_2$  (YSZ) substrate by magnetron sputtering and etching of the film. CEBs have been fabricated using an Al multilayer structure by a self-aligned shadow evaporation technique on Si substrate. Both receiver and oscillator have been located inside the same cryostat at 0.3K and 2.7K plates, respectively.

**Keywords:** anisotropic high- $T_c$  grain-boundary, YBCO Josephson oscillator, cold-electron bolometer, sine-Gordon equation

## 1. Introduction

The high precision measurements of the polarization in the cosmic microwave background (CMB) radiation is one of the major tasks in modern cosmology, needed to detect primordial B-modes. B-mode is a curl component of the polarization of CMB, which, as believed, left by the primordial gravitational waves during the inflation stage of the Universe evolution. Predicted by theory, it is to be detected as a sufficient evidence of the inflationary epoch in the early Universe [1].

The development of multichroic focal planes for measurements of the CMB is important for increasing the sensitivity of an experiment as well as for removing the contamination due to galactic foregrounds, which is becoming the limiting factor in CMB measurements [2]. The cold-electron bolometer (CEB) is an attractive candidate for these measurements because the decoupling of the phonon and electron subsystems in the tiny absorber gives it such advantages as high sensitivity and high saturation power [3,4] as well as the immunity to cosmic rays [5]. CEBs can be used for on-chip LC-filtering due to a series resonance of the capacitance of SIN junctions and the kinetic inductance of the NbN strip [6–8] or the reactance of slot antennas connected by coplanar lines [9,10]. This property is used for the creation of multichroic pixels with CEBs.

The most actual task for the elaboration of multichroic bolometric systems is developing of the broadband radiation source with narrow spectral linewidth, placed inside a cryostat to avoid multiple reflections and sensitivity loss due to open windows. In recent years frequency calibrations of CEBs have been carried out using external sources of the THz range [11,12] or filtered broadband thermal sources [13,14]. These solutions are not very suitable when repetitive calibrations in a wide range of frequencies for different resonant structures are required. Here we look at a calibration source based

on the long YBCO Josephson junction (JJ), having a continuous frequency tuning in a wide frequency range from 0.1 to 2 THz.

High critical temperature bicrystal Josephson junctions can be used for THz frequency band oscillators, detectors and Hilbert spectrometers, as was shown, for example, in [15,16]. Even relatively weak radiation of a long YBCO JJ can be useful for spectral calibration of highly sensitive cryogenic detectors. Josephson generators are one of the most convenient sources of GHz and subTHz signals because they have the potential to generate in a wide frequency range, and their main frequency is easily determined by the Josephson relation. Measurement of high-temperature JJs, both  $\text{YBa}_2\text{Cu}_3\text{O}_{7-\delta}$  and  $\text{Bi}_2\text{Sr}_2\text{CaCu}_2\text{O}_8$ , requires the use of very sensitive detectors, such as integrated superconducting heterodyne receivers [17–19], bolometers [20,21], single-photon detectors [22]. For the analysis of planar bicrystal junctions in all works short junctions were used. In this work, we analyze the regime that occurs only in a long JJ under the effect of the magnetic field, called a "traveling wave" or "flux flow" regime. The study of the flux-flow regime arising in JJ is a subject of practical interest. In a long JJ (length,  $L \gg \lambda_J$ , where  $\lambda_J$  is the Josephson penetration depth), placed in an external magnetic field, the fluxons can be created at one edge of the junction and after movement along the junction radiated at the opposite edge, creating the so-called fluxon motion mode. When the fluxon velocity  $u$  becomes close to the EM wave phase velocity  $\bar{c}$ , a current step (velocity-matching or flux-flow step) appears at the current-voltage (IV) characteristic. While for low- $T_c$  Josephson junctions this regime has been investigated both experimentally [23–30] and theoretically [32–41], there are just a few works for high- $T_c$  JJs in this regime [44–47], and their analysis was limited to the study of dc characteristics.

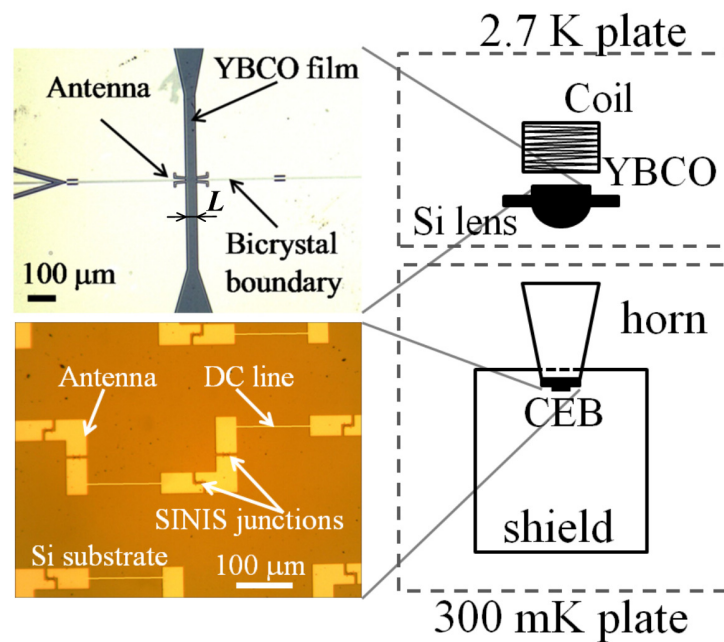
This work aims to study theoretically and experimentally the flux-flow regime and THz radiation, arising in this regime, of long YBCO bicrystal Josephson junction (YBCO FFO), by means of the CEB receiver.

## 2. Experimental Setup

CEB represents SINIS (SIN - superconductor-insulator-normal metal) junctions  $\text{Al}/\text{Al}_2\text{O}_3/\text{Al-Fe}/\text{Al}_2\text{O}_3/\text{Al}$  with a normal metal tiny nanoabsorber made of aluminum with suppressed superconductivity due to underlayer of Fe. The saturation power for one CEB is about 0.5 pW. Taking into account the expected power load, the 2-dimensional array of CEBs [48] has been realized as a meander-type structure [3,12]. The receiving system represents a single pixel for the Olimpo balloon experiment, optimized for power loads up to 100 pW. The unit cell of dipoles is a modification of the dense rectangular grid, distributed in a more sparse way over the unit cell [48]. The serial and parallel DC connections of CEBs are optimized for impedance matching and minimal overall system noise [3]. The pairs of  $\lambda/2$  dipoles sensitive to both orthogonal linear polarizations are connected to each other by dc lines with 1  $\mu\text{m}$  width. The impedance of each bolometer comes from a series connection of a 30 Ohm resistance and a 55 fF capacitance. In difference with the original design [3,12], the unetched 280  $\mu\text{m}$  substrate has been used to match the bolometer bandwidth with the YBCO oscillator antenna bandwidth in the range 240-280 GHz.

The long grain boundary Josephson junctions (GBJs) were fabricated by on-axis dc magnetron sputtering [49] of  $\text{YBa}_2\text{Cu}_3\text{O}_{7-\delta}$  thin films on the surface of  $24^\circ[001]$ -tilt  $\text{Zr}_{1-x}\text{Y}_x\text{O}_2$  bicrystal substrates and further etching. The length of the junctions  $L$  along the grain boundary (sample photo in Figure 1) was 50  $\mu\text{m}$ , the thickness was 0.3  $\mu\text{m}$ . We have obtained critical current density 370  $\text{kA}/\text{cm}^2$  and the  $I_c R_n$  product of 1.54 mV for  $T = 6$  K. The junctions were very long since their lengths are much larger than the Josephson penetration depth  $\lambda_J = \sqrt{\Phi_0/(2\pi\mu_0 J_c d)} = 0.6 - 0.9 \mu\text{m}$  ( $T \sim 6\text{K}$ ), which determines the size of a fluxon in the junction. Based on the analysis of the transport properties, the best structures were selected and located at the center of the Si lens for effective radiation. The perpendicular to the grain boundary magnetic field  $B_c$  of the order of tenths Gauss was produced by a copper wire coil with many adjacent loops (solenoid). The coil inner diameter of 10 mm was at least one order of magnitude larger than the junction length. Therefore, the magnetic field in the vicinity of the junction was assumed to be nearly uniform [49].

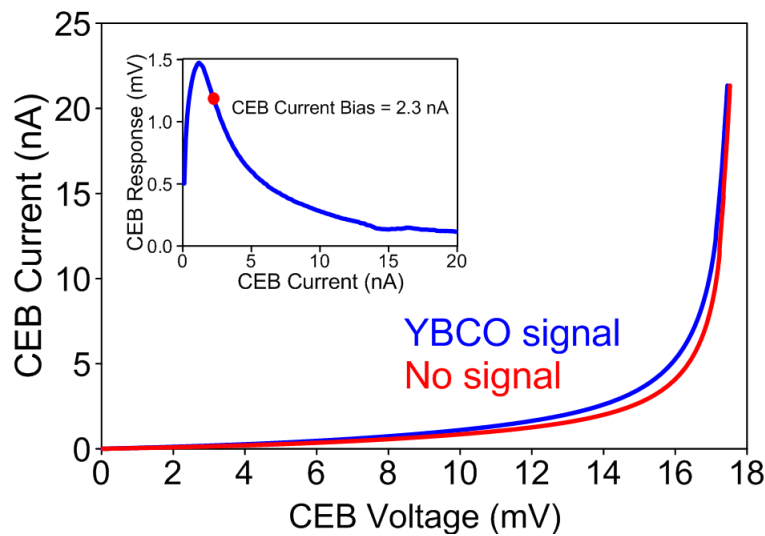
In Figure 1 the scheme of the experimental setup is presented. The distance between the detector (CEBs) and the source (YBCO) is 3 cm. The YSZ substrate with the YBCO GBJ was attached to the Si hyperhemisphere lens with 4 mm diameter at the 2.7 K plate of 3He refrigerator. The radiation from YBCO goes after the lens through the copper horn to the Si substrate with the CEBs from the bottom side. The receiving detector consists of an array of 192 CEBs, connected in 4 parallel rows to match with JFET amplifier impedance [3]. The array is surrounded by a copper shield [14] to avoid radiation from other directions and is attached to the 0.3 K cryostat plate.



**Figure 1.** The view of the experimental setup, its schematic representation and samples design.

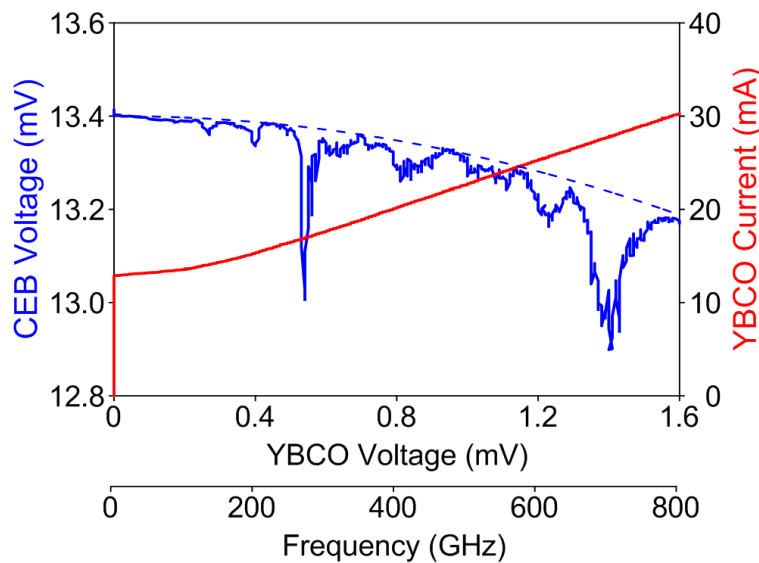
### 3. Experimental Results

In Figure 2 the current-voltage characteristics of CEBs are shown for the case of no signal (no bias of YBCO oscillator) and the case under YBCO JJ power load. Bolometer response is defined as a voltage difference at a fixed bias current through the CEBs array with and without the JJ radiation. Based on the response characteristic (the inset of Figure 2) the bias current for the bolometer has been chosen aside from the maximum response since there is a minimal value of noise-equivalent-power [3].



**Figure 2.** Current-voltage characteristic of bolometer for the case of no signal and under the YBCO JJ radiation. The inset: CEBs response as a function of bias current. The mark corresponds to the used bias.

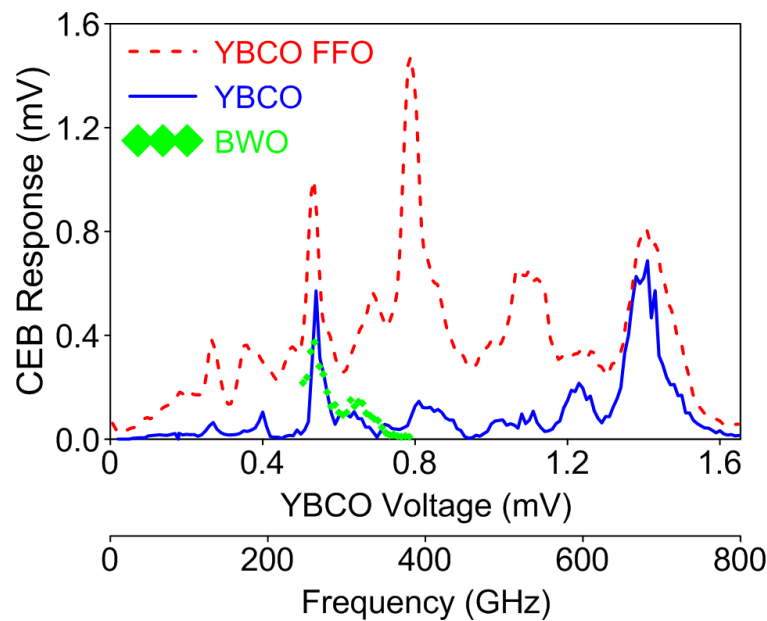
Changing the current through the Josephson junction (for zero current through the coil, creating the magnetic field), the signal from the bolometer and the voltage on the YBCO oscillator (which is connected with the oscillation frequency via the Josephson relation) were measured, see Figure 3. The detected signal consists of two components. The first one, smooth, corresponds to infrared radiation from an overheated Josephson junction and magnetic coil. It can be well described by a spline line  $V_{CEB} = aV_{YBCO}^2 + bV_{YBCO} + c$  (dashed curve in Figure 3). The second component, uneven, is a generation signal at the Josephson frequency  $f = 2eV_{YBCO}/h$  and is sensitive to a magnetic field. To reduce the first component, the measurements were carried out as quickly as possible, which is allowed without loss of accuracy thanks to the fast response of CEBs. The adjustment of JJ bias and measurement time of the bolometer response to the JJ radiation of a given frequency is milliseconds, while the duration of the thermal response due to system overheating is seconds.



**Figure 3.** Left: CEBs voltage (solid curve) and a fitting spline (dashed curve). Right: current-voltage characteristic of YBCO oscillator.

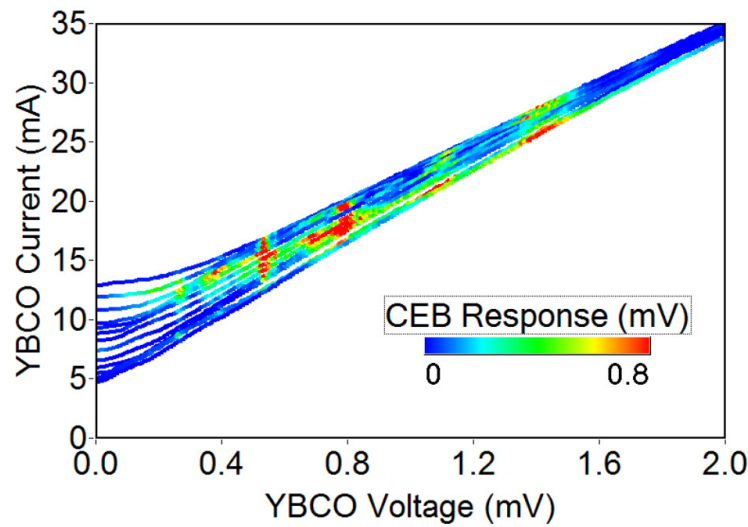
Subtracting the component of the background heating signal, the response of the bolometer to the YBCO JJ radiation as a function of frequency has been obtained (see blue solid curve in Figure 4,

marked as YBCO, for the case of zero magnetic field when the only bias current through JJ was varied). It is seen that the response consists of several peaks with different heights. Comparing it with the CEBs amplitude-frequency characteristic (AFC) obtained by the calibrated backward-wave oscillator (BWO) source (green symbols in Figure 4), one can conclude that the peak positions are determined both by characteristics of the receiving and the radiating systems. If in addition to bias current, one starts to vary the magnetic field (current through the coil), the response grows significantly and larger peaks can be visible (red dashed curve in Figure 4). It should be noted that the CEB AFC measurements were performed with BWO source placed outside the cryostat, and the signal was strongly attenuated both by attenuators placed at BWO, and also by null-density filters at the cryostat windows to prevent from 0.3 K plate overheating due to incoming THz signal. The internal inhomogeneity of the BWO amplitude–frequency characteristic was properly taken into account when plotting the corresponding curve of Figure 4.



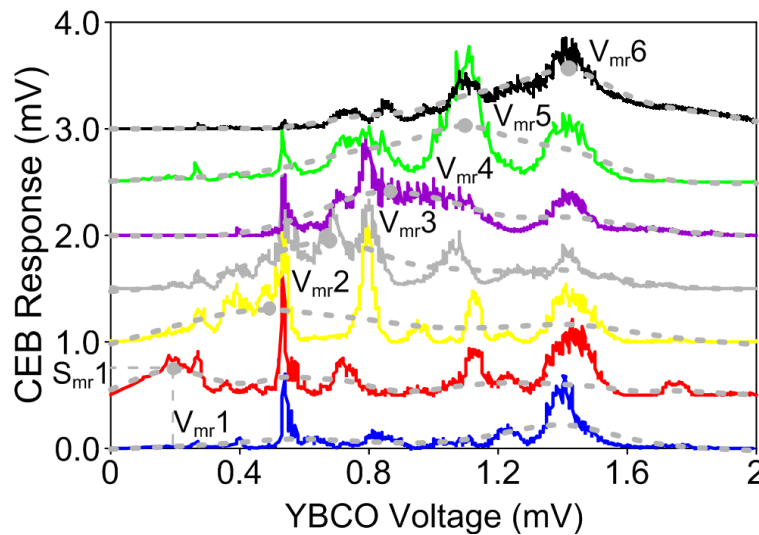
**Figure 4.** CEBs response depending on YBCO voltage (oscillation frequency). Comparison of the CEBs signal from BWO and YBCO sources. Signatures of YBCO and YBCO FFO correspond to the case of zero magnetic field and case of magnetic field variation.

Figure 5 presents the experimental IV curves of YBCO JJ for various values of the applied magnetic field. The color indicates the level of CEBs response. We observe field dependent steps, characteristic to the travelling wave regime in a long Josephson junction. It should be noted that in difference with Nb junctions [38], for YBCO structures, due to larger damping, it is rather difficult to distinguish between various step types, such as displaced linear slopes, Fiske steps and velocity matching (VM) steps [50,51]. The separate peaks, repeated at the same frequency for all magnetic fields, are attributed to overlapping responses between different harmonics of antennas of YBCO oscillator and CEBs array. The AFC of the YBCO antenna has recently been measured in [51] from the height of Shapiro step in the frequency range from 240 to 350 GHz with the same BWO as a radiation source. The maximum response has been observed from 250 to 280 GHz, which corresponds to the first harmonics of the YBCO JJ dipole antenna.



**Figure 5.** The experimental  $IV$  curves of bicrystal junction  $L = 50 \mu\text{m}$  correspond to the increasing magnetic field (from top to bottom). The color indicates the level of CEBs response.

Figure 6 shows the CEBs response (dependent on the absorbed power) for several values of the external magnetic field. For convenience, the curves starting from the second one are shifted up by 0.5 mV relative to the previous one. To characterize this picture, let us smooth out the dependences (grey dashed curves in Figure 6) and find the voltage of the local maximum of the response  $V_{mr}$  and the value of response  $S_{mr}$ . It can be seen that for larger magnetic fields, the position of maxima is shifted towards higher voltages as it must in the traveling wave regime, see also Figure 5.

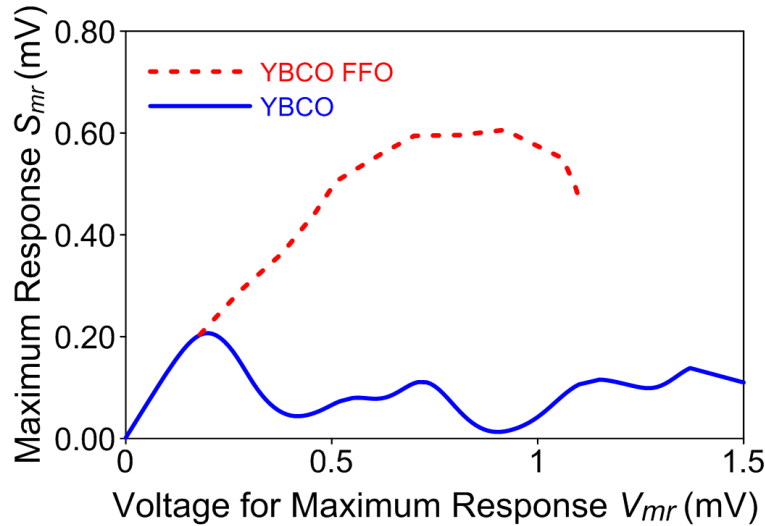


**Figure 6.** CEBs response for increasing magnetic fields through the YBCO oscillator. For convenience, the curves starting from the second one are shifted up by 0.5 mV relative to the previous one. Marks correspond to the local maximum of each smoothed characteristic.

An array of fluxons, which for a high magnetic fields transforms into the travelling wave, propagates along the junction with the phase velocity  $u = V_{dc} / (d\mu_0 H_e)$  [45], where  $V_{dc}$  is the average voltage across the junction,  $H_e$  is the external magnetic field applied in the direction perpendicular to the grain boundary,  $d$  is the effective magnetic thickness of the barrier and  $\mu_0$  is the magnetic constant. The voltage at the top of the flux-flow step on the  $IV$  characteristic is determined by the VM condition: the velocity  $u$  approaches the Swihart velocity  $\bar{c}$  and, hence,  $V_{vm} \approx \bar{c}d\mu_0 H_e = \bar{c}dB_e$ .



This ratio is confirmed experimentally: the voltage position of the step for larger fields depends linearly on the applied field [45,50]. The voltage range from 0.2 to 1.1 mV corresponds to Josephson frequencies ranging from about 100 to 550 GHz. The VM step becomes smaller and wider as the voltage is increased. This is expected from the increasing surface losses at higher frequencies [38]. The same picture is observed for the received power (CEBs response): the applied magnetic field allows to increase the response voltage  $V_{mr}$  in a wider frequency range.



**Figure 7.** The maximum response depending on YBCO voltage for bicrystal junction with the length  $L = 50 \mu\text{m}$  for phase rotation regime (blue solid curve) and traveling wave regime (red dashed curve).

To find out what the maximum power is possible for a given voltage (frequency) in the travelling wave regime, it is necessary to investigate the  $S_{mr}(V_{mr})$  characteristic (red dashed curve in Figure 7). Each point corresponds to a different magnetic field value. The dependence of the CEBs response on the YBCO voltage  $S_{mr}(V_{mr})$  has a flat maximum at the frequency range  $\sim 350\text{-}500$  GHz. The form of this curve also depends on surface losses, the antenna system, impedance matching, etc. It is interesting to compare the power from the JJ, operating in the phase rotation regime, when the external magnetic field is zero and the frequency is tuned by the bias current variation only (blue solid curve in Figure 7), and YBCO FFO, operating in the traveling wave regime with the frequency tuned by both bias current and magnetic field variation. One can see that in the latter case the oscillation power increases and can be observed in a much wider frequency range. Therefore, this experimental result is a confirmation of recent theoretical observation that the oscillation power in the case of lag-synchronization (occurring in the travelling wave regime) can be several orders of magnitude larger than for perfect in-phase synchronization of chain elements [52]. These results also show the advantages of using long Josephson junctions over short ones to develop an effective THz generator. It should be noted that in the previous work on detecting the generation of a short Josephson junction using a CEB [16], it was shown that when a magnetic field is applied to the JJ, the amplitude of the received signal decreases, while in our case the amplitude grows.

#### 4. Theory

Theoretical analysis was based on the sine-Gordon equation [49,53]:

$$\phi_{tt} + \alpha\phi_t - \phi_{xx} = \beta\phi_{xxt} + \eta - \sin\phi, \quad (1)$$

where indices  $t$  and  $x$  denote temporal and spatial derivatives,  $\phi$  is the phase order parameter. Space and time are normalized to the Josephson penetration length  $\lambda_J$  and to the inverse plasma frequency  $\omega_p^{-1}$ , respectively,  $\alpha = \omega_p/\omega_c$  is the damping parameter,  $\omega_p = \sqrt{2eI_c/\hbar C}$ ,  $\omega_c = 2eI_c R_N/\hbar$ ,  $\beta$  is the

surface loss parameter,  $\eta$  is the bias current normalized to the critical current. The boundary conditions that simulate simple RC-loads, see Ref.s [34,38,40,41], have the form:

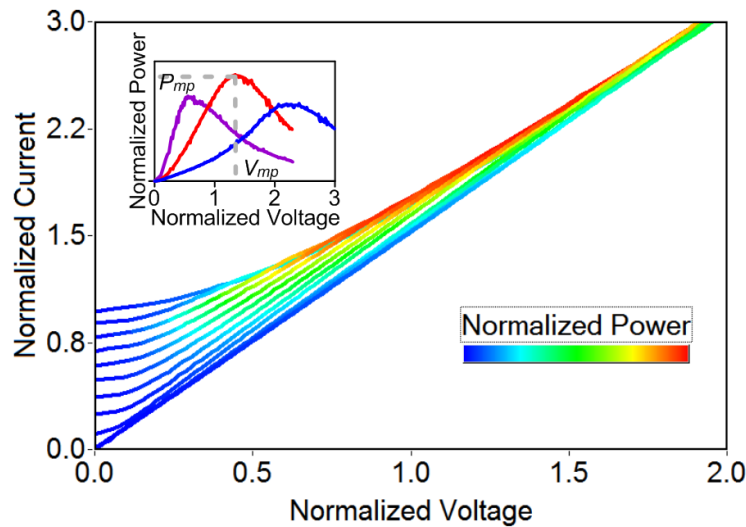
$$\phi(0, t)_x + r_L c_L \phi(0, t)_{xt} - c_L \phi(0, t)_{tt} + \beta r_L c_L \phi(0, t)_{xtt} + \beta \phi(0, t)_{xt} = \Gamma, \quad (2)$$

$$\phi(L, t)_x + r_R c_R \phi(L, t)_{xt} + c_R \phi(L, t)_{tt} + \beta r_R c_R \phi(L, t)_{xtt} + \beta \phi(L, t)_{xt} = \Gamma. \quad (3)$$

Here  $\Gamma = H_e / (\lambda_J J_c)$  is the normalized magnetic field. The dimensionless capacitances and resistances,  $c_{L,R}$  and  $r_{L,R}$ , are the FFO RC-load placed at the left (output) and at the right (input) ends, respectively. The power  $P$  of radiation, emitted from the junction output edge is normalized to the Josephson power  $P_J = V_J^2 / Z_0$ , where  $Z_0$  is the characteristic impedance of the junction.

The computer simulations of the sine-Gordon equation are performed for the following parameters: damping  $\alpha = 1.5$ , surface loss  $\beta = 0.1$ , and dimensionless junction length  $l = 70$ .

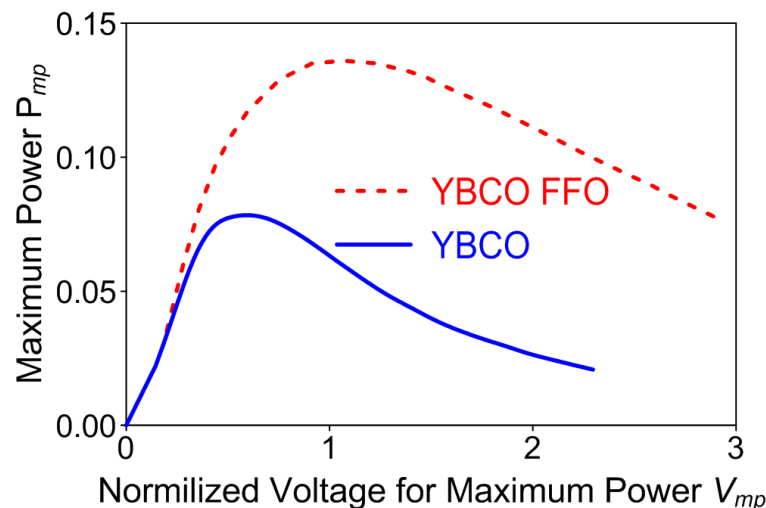
Figure 8 shows the theoretical IV curves for various values of applied magnetic field  $\Gamma$ . The color indicates the level of radiation power  $P$ . In the present case, the antenna bandwidth is not considered, assuming that the junction is perfectly matched to a load in the whole frequency range. We observe the regime of a continuous flow of fluxons, which for larger magnetic fields smoothly transforms into travelling wave regime. The inset of Figure 8 shows the radiated power level for several values of the magnetic field. Here we marked the voltage position of the maximum power as  $V_{mp}$  and the maximum power as  $P_{mp}$ .



**Figure 8.** The theoretical IV curves correspond to increasing magnetic field  $\Gamma$  (from top to bottom). The color indicates the level of radiated power. The inset: Power  $P$  for various magnetic fields ( $\Gamma = 0.6; 1.6; 2.6$ ) depending on voltage.

Figure 9 shows the dependence of the power level versus voltage  $P_{mp}(V_{mp})$  for zero external magnetic field (blue solid curve) and nonzero external magnetic field, leading to a traveling wave regime (red dashed curve). Both theoretical curves show the behavior, qualitatively similar to the experiment (see Figure 7), they both have maxima, but the maximum, corresponding to YBCO FFO, is wider and reaches larger values. Therefore, such dependences demonstrate the advantage of a long YBCO JJ, operating in the traveling wave regime, compared with short and long junctions operating in the phase rotation regime, as THz broadband sources.





**Figure 9.** The maximum value of power level depending on voltage for phase rotation regime (blue solid curve) and traveling wave regime (red dashed curve).

## 5. Conclusions

The investigation of the response of a Cold Electron Bolometer receiver on the THz radiation of long  $24^\circ[001]$ -tilt  $\text{YBa}_2\text{Cu}_3\text{O}_{7-\delta}$  bicrystal grain-boundary junctions has been performed. The investigation of maximum oscillation power versus magnetic field is performed both experimentally and theoretically and its dependence corresponds to the traveling wave regime. While the antennas of both emitting and receiving systems were tuned in the frequency range from 250 to 320 GHz, the visible response has been detected in windows up to 0.8 THz. Although the maximal received power as estimated from fitting of CEBs IV response is rather low and of the order of 10 pW, these results can be explained by poor matching of YBCO junction with its antenna due to unknown impedance and a difference in the dielectric constant of the JJ YSZ substrate and Si lens material. Despite that the considered sample of the long YBCO JJ has low generation efficiency, such oscillators can be useful for spectral calibration of low-temperature bolometers, receivers, and single-photon detectors.

**Author Contributions:** L.R. contributed experiment planning, experiment measurements, data analysis and manuscript preparation. A.P. contributed experiment measurements, writing–review and editing. A.G. contributed methodology, experiment planning, manuscript preparation. D.M. contributed research sample preparation. A.P. contributed research sample preparation. V.Z. contributed experiment planning. L.K. contributed supervision, writing–review and editing. All authors have read and agreed to the published version of the manuscript.

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