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A room temperature bolometer for terahertz coherent and incoherent detection

Sergey Cherednichenko, Arvid Hammar, Stella Bevilacqua, Vladimir Drakinskiy, Jan Stake, *Senior Member, IEEE*, and Alexey Kalabukhov

***Abstract*—We present a novel room temperature bolometer with nanosecond response that can be used both for coherent and incoherent detection through the entire terahertz frequency range. A responsivity of up to 15 V/W, and a noise equivalent power (NEP) ~ 450 pW/Hz$^{0.5}$ were measured at modulation frequencies from 0.5 kHz to 100 kHz. A conversion gain of -28 dB was demonstrated at an intermediate frequency of 20 MHz with a Local Oscillator power of 0.74 mW. Possible improvements of the bolometer characteristics are discussed.**

***Index Terms*—Bolometer, mixer, terahertz (THz), submillimeter, YBCO. room temperature detector.**

I. INTRODUCTION

THz waves (300 GHz-10 THz) have a wide area of applications, e.g. security and medical imaging, gas and solids spectroscopy, communication, etc [1], [2]. The progress in those areas depends on the availability of the key components: detectors, sources, filters, etc. A great progress in electro-optical THz wave generation/detection has led to a breakthrough in the development of pulsed THz systems. For example, THz time domain spectrometers offer a wide frequency coverage, which is a valuable feature for spectroscopy of solids and large molecules (e.g. DNA) [3], [4].

Continuous wave (CW) systems have been extensively used in radio astronomy, where many cryogenic detectors have been developed, offering a high power sensitivity [5]. Apart from radio astronomy, where sensitivity is the main drive for the choice of a detector, many other applications are critically dependent on compact, non cryogenic (or moderately cooled) THz detectors. Currently, such detectors are limited to Schottky diodes that are the most sensitive room temperature detectors practically available today for frequencies up to at least 1THz [6]. Schottky diodes are used both for coherent and direct detection. As an alternative, tunnel diodes have shown a high responsivity in the millimeter wave range, although they have not been extended to the THz range yet [7].

Room temperature bolometers are widely used in IR cameras. They are primarily based on VOx films that are thermally isolated on a thin membrane. With an adapted optics, such cameras have also been shown to operate at 4.3THz [8]. The discussed bolometers are known to be slow, with a typical response time of several ms [9]. Moreover, at frequencies lower that 4 THz, antenna integrated bolometers would be required, because the radiation wavelength becomes much greater than the bolometer patch size (~40 μm). Using an air-bridge approach, a microsecond response time was reported for Nb antenna coupled bolometers [10].

Recently, we reported on fast antenna coupled superconducting bolometers, which are based on high-temperature superconducting films of $YBa_2Cu_3O_7$. At a 77K operation temperature, they achieve a NEP of ~ 20pW/Hz and a voltage responsivity of ~ 190V/W in a frequency range of 0.3-1.6THz [11]. The response time was approximately 1ns.

In this paper we demonstrate that using a similar antenna-integrated YBCO bolometer, a ns-response time and a high sensitivity are feasible at room temperature operation. The bolometers are placed on a bulk substrate, and, therefore, they are very robust. In fact, bolometer operation temperature is not critical for the device performance. We investigate these devices both as direct detectors as well as mixers.

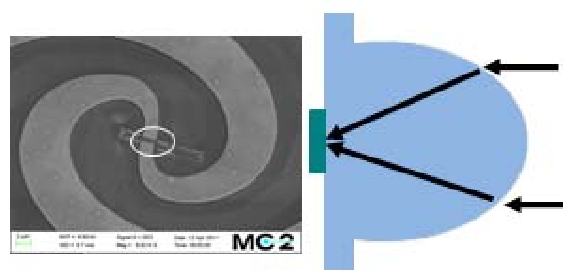

Fig. 1. A quasioptical THz bolometer is integrated with a spiral antenna on a sapphire substrate. The bolometer chip is glued to a Si lens.

II. DEVICE FABRICATION

Bolometers were fabricated using a 50-nm-thick YBCO film. The film was made on a sapphire substrate with a CeO_2 buffer layer using pulsed laser deposition. The critical temperature of the YBCO film is about 88 K. A large Temperature Coefficient of Resistance (TCR) in the normal state (*T*>88K) was our prime interest. The YBCO film was patterned as a microbridge to overlap with the antenna made of 350 nm thick gold film via UV photolithography (see Fig. 1). The bolometer area between antenna pads was (the width, *w*, times the length, *l*) 2 μm x 1 μm, 3 μm × 1 μm, and 4 μm × 1 μm. The choice of a logarithmic spiral antenna

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The authors are with Chalmers University of Technology, Department of Microtechnology and Nanoscience, SE-412 96, Göteborg, Sweden (corresponding author phone: +46-31-7728499; fax: +46-31-164513; e-mail: serguei@ chalmers.se).

was motivated by its real impedance of 90 Ω in a wide frequency range [12]. A scanning electron microscope image of a bolometer between antenna terminals is shown in Fig.2. After the fabrication, the substrate was diced for single bolometer chips. The chips were clamped to the backside of a 12-mm elliptical silicon lens, forming a quasioptical THz detector. In the detector block, the readout was arranged via a coaxial waveguide and a bias-T.

The resistance versus temperature for the bolometers is shown in Fig.3.

III. Experimental technique

For the responsivity measurements, amplitude modulated signal sources at 100 GHz (a Gunn diode oscillator) and 330 GHz (a Backward Wave Oscillator) were used. The sources were equipped with horn antennas. A Teflon lens focused the beam on the Si lens/bolometer. The optical coupling efficiency to the spiral antenna bolometers on a silicon lens has been discussed in [11]: ~4-5dB, that accounted for the Si lens reflection losses, polarization losses, and beam coupling losses. In this paper, THz power, absorbed in the bolometer, was used for the responsivity calculation. The absorbed power was obtained using the isothermal technique [13]. We also verified this method using a 1GHz signal, which was fed into the bolometer via a coaxial cable, i.e. no optical losses were present. In this case, the absorbed power (from the isothermal technique) corresponded very well to the output power of the signal generator.

The bolometers were biased with a constant current. Both the voltage response to the THz signal and the bolometer noise voltage (THz signal blocked) were measured using a lock-in amplifier.

The mixer conversion gain was measured at 90 GHz, using a second 90 GHz source (an active multiplier) as a Local Oscillator (LO). A low noise amplifier (100 K input noise temperature) amplified the IF signal before it was measured using a spectrum analyzer. The LO power was estimated with the same method as the power of the signal source.

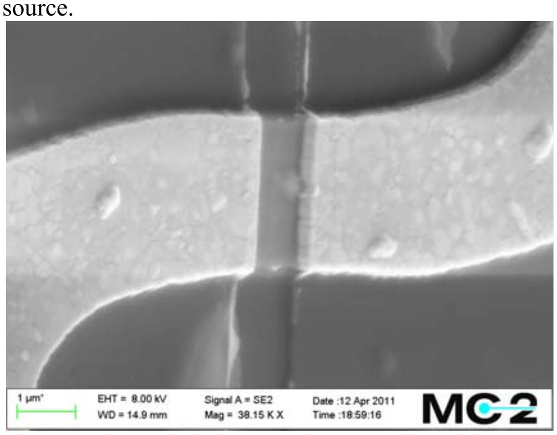

Fig. 2. SEM image of a bolometer at the center of the spiral antenna.

IV. Bolometric detector

A. Direct detector

At modulation frequencies $\omega << 1/\tau$, where τ is the bolometer response time, the voltage responsivity of the bolometer to an amplitude modulated RF signal can be obtained from a system of two thermal balance equations:

$$G \cdot \Delta T_1 = i^2 \cdot R_1 \quad (1a)$$
$$G \cdot \Delta T_2 = i^2 \cdot R_2 + P_{RF} \quad (1b)$$

where G is the thermal conductance from the bolometer to the heat sink (the substrates and the contact pads), $\Delta T_{1,2}$ are the bolometer temperature rise (relative to the substrate temperature) with and without the RF power, i is the dc bias current, $R_{1,2}$ are the bolometer dc resistance with and without the RF power, P_{RF} is the RF power absorbed in the bolometer. Equations (1a) and (1b) represent thermal balance with and without applied RF power.

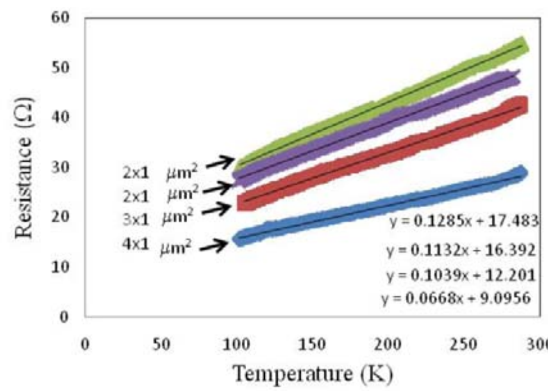

Fig. 3. Resistance versus temperature for 4µm x1µm, 3µm x1µm, and 2µm x1µm bolometers. Equations of the fitting lines are given in the legend.

The bolometer is assumed to be constant current biased. The voltage responsivity is defined as a ratio of the bolometer voltage swing to the absorbed RF power [14]:

$$R_V = \frac{i \cdot \alpha \cdot R}{G - i^2 \cdot \alpha \cdot R} \quad (2)$$

where $\alpha \equiv \partial R/\partial T \cdot 1/R$ is the TCR. As follows from Fig.3, in the temperature range from 100K to 300K $\alpha \times R$ is temperature independent. However, $\alpha \times R$ is larger for higher resistance devices. On the contrary, α is approximately constant for all devices discussed here. At modulation frequencies that exceed $1/\tau$, the responsivity reduces as $1/(1+\omega^2\tau^2)^{0.5}$ [14].

The dominant noise contributors in a bolometer are: the Johnson noise, U_{NJ}, the phonon noise, U_{NF}, and the low frequency flicker noise, U_{NFL}. For a 1 Hz (post-detection) bandwidth, the corresponding noise voltages are [14]:

$$U_{NJ} = (4RkT)^{0.5} \quad (3)$$
$$U_{NF} = (4kT^2G)^{0.5} S_V$$
$$U_{NFL} = i^x f(\omega)$$

where x (>0) depends on the device nature, and $f(\omega)$ is the flicker noise frequency dependence. The Noise Equivalent Power (NEP) is calculated as:

$$NEP^2 = 4RkT/R_V^2 + 4kT^2G + i^{2x} f(\omega)^2/R_V^2 \quad (4)$$

B. Mixer

The theory of bolometric mixers has been discussed e.g. in [15]. Interference of the Local Oscillator (LO) and the Signal (S) waves results in an amplitude modulation of the signal at an Intermediate Frequency (IF), $\omega_0=|\omega_{LO}-\omega_S|$. It has been shown [15], that the mixer conversion gain is :

$$G_m = \frac{2\cdot i^2\cdot C_0^2\cdot P_{LO}\cdot R_L}{(R_L+R)^2}\cdot\left(1-i^2\cdot C_0\cdot\frac{R_L-R}{R_L+R}\right)^{-2} \quad (5)$$

where $C_0=\partial R/\partial T\cdot 1/G$ is the self-heating parameter, R_L is the IF load impedance (50 Ohm in most cases). Using the definition of the self-heating parameter, the expression for the voltage responsivity (2) can be simplified to:

$$R_V = i\cdot C_0 \quad (6)$$

From the analysis of equations (2) and (5) we conclude that the conversion gain is proportional to the square of the responsivity, $G_m \sim R_v^2$. In (5), we assume that C_o is an invariant of both i and P_{LO}. Because the temperature of the bolometer increases when either the bias current or the LO power is applied, the mentioned condition is valid only if the thermal conductance G is temperature independent (see the definition of C_o above).

V. Measurements of the Thermal Conductance

Using equation (1a), the thermal conductance G can be derived from IV-curves and $\partial R/\partial T$ (Fig.3). In Table I we summarize the thermal conductance for several devices that were measured at room temperature. The G scales approximately with the bolometer area.

TABLE I. THERMAL CONDUCTANCE BETWEEN THE BOLOMETER AND THE HEAT SINK.

Device size (μm^2)	4×1	3×1	2×1
G at 292K (×10^{-4} W/K)	1.45	0.86	0.53

For a 4μm×1μm bolometer, the thermal conductance versus temperature was measured at several temperatures down to 112K, see Table II.

If the heat flow into the substrate is the dominant bolometer cooling path, then G equals the ratio of the bolometer area to the bolometer/substrate thermal boundary resistance, R_{bd}:

$$G = A/R_{bd} \quad (7)$$

A temperature independent thermal boundary resistance for YBCO films on a sapphire substrate has been reported earlier, although for much larger structures [16]. From these facts we can conclude that for our micrometer scale YBCO bolometers the cooling occurs mainly into the substrate and the heat diffusion into the contact pads is still not visible.

TABLE II.
THERMAL CONDUCTANCE BETWEEN THE 4μm×1μm BOLOMETER AND THE HEAT SINK VERSUS TEMPERATURE.

T (K)	293	218K	171K	112K
G×10^{-4}, W/K	1.66	1.58	1.42	1.66

Because the G is temperature independent, both the LO power and the bias current can be increased in order to maximize the mixer conversion gain. This statement is also true for the bolometer responsivity (although, for the bias current only). The upper limits for both i and P_{LO} will be discussed in Section VII.

VI. Responsivity Measurements

In order to correlate variations of the thermal conductance to the bolometer responsivity, we compared the measured responsivity of devices of several sizes at the same bias current, 1mA (Table III)

TABLE III
THE RESPONSIVITY MEASURED AT 330GHZ.

$w\times l$, μm^2	R, Ohm	U_{LIA} (μV) (at290K,1mA)	R_V (V/W) at i=1mA	$Pabs$, μW
4x1	30	17	0.63	63
3x1	45	38	1.40	63
2x1	55	65	2.40	67
2x1	53	30*	3.00	25*

*at 1GHz RF.
Ulia is the voltage response (measured with the lock-in) for the specified absorbed RF power P_{ABS}.

Most of the measurements were done at 330GHz, except for one bolometer, which was tested at 1GHz.

At the constant bias current the responsivity scales inversely with the bolometer area (Table III), which is in agreement with our measurements of the thermal conductance for the same devices.

The measured responsivity scales linearly with the bias current (Fig.4, symbols), as is expected from (2) (Fig.4, solid lines). For large bias currents, the $R_v(i)$ deviates from a linear function, because the denominator in (2) starts to decrease.

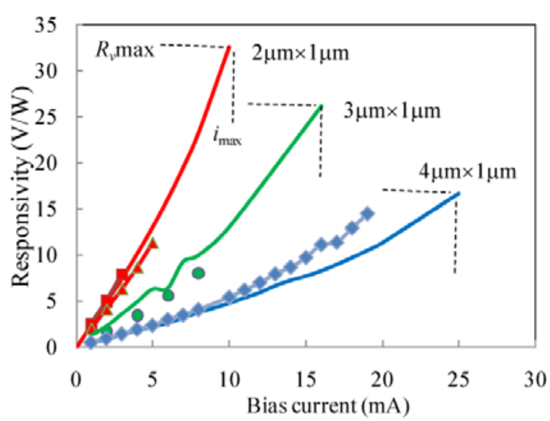

Fig. 4. Voltage responsivity of YBCO bolometers at room temperature calculated from the devices dc parameters (solid lines) and measured (dots). The maximum bias currents and the corresponding maximum responsivity are marked by the dashed lines.

A nearly constant responsivity from 300GHz to 1.6THz for the discussed YBCO bolometers was reported in [11] for an operation temperature of 77K. At room temperature, the bolometers are expected to have similar RF bandwidth that is limited by the antenna.

VII. Responsivity limits

A. Direct detection

The voltage responsivity (2) of a bolometer is proportional to the bias current, the temperature derivative of the resistance, $\partial R/\partial T$, and inversely proportional to the thermal conductance to the substrate. The latter is proportional to the device area; such that a smaller device should provides a higher responsivity. In Fig. 4, we plot the calculated responsivity versus the bias current for several devices (solid lines). For the calculations we used values of G as discussed in the previous sections. In order to obtain a higher responsivity the bias current can be increased, although only until the device breaks. Our experience shows that the breakdown voltage scales with the device size and it seems to be caused by device overheating. The rise of the bolometer temperature over the substrate temperature can be calculated from equations (1):

$$\Delta T = \frac{i^2 \cdot R}{G - i^2 \cdot \alpha \cdot R}$$

A rapid increase of the bolometer temperature occurs when the $i^2 \cdot \alpha \cdot R$ term approaches the value of G (commonly discussed as thermal runaway for current biased bolometers). We introduce a bias current limit as:

$$i_{max} = (0.3\, G / \alpha R)^{0.5} = (0.3\, w^2 d / (R_{bd} \cdot \alpha \cdot \rho))^{0.5} \quad (8)$$

Using present device parameters, it can be calculated that the maximum current corresponds approximately to a bolometer temperature rise of 150- 200 K.

We calculate the maximum bias current values for the devices and show them in Fig. 4 together with the corresponding maximum values for the responsivity.

As expected, larger bolometers allow for a larger bias current. However, the resulting maximum responsivity increases as the bolometer size is reduced. A responsivity of up to 33 V/W can be achieved for a 2μm×1μm bolometer at the room temperature at the 11 mA bias current.

For the maximum bias currents of 11mA, 16mA, and 26mA for the discussed bolometers of 2μm×1μm, 3μm×1μm, and 4μm×1μm in size, the corresponding values for the dissipated dc (Joule) power are: 9mW, 16mW, and 27mW.

B. Mixer

In the case of heterodyne detection, both the bias current and the LO power act towards a higher conversion gain. For safe operation of the mixer, the total dissipated power (P_{dc}+P_{LO}) has not to exceed the maximum value discussed in the previous Section. From (5) it is also seen that the conversion gain is proportional to a product $i^2 \times P_{LO} = P_{dc} \times P_{LO} / R_0$. For a constant $(P_{dc}+P_{LO})=P_{max}$, the $P_{dc} \times P_{LO}$ product is maximized when $P_{dc}=P_{LO}= 0.5\, P_{max}$.

Using measured device parameters, the computed maximum total dissipated power, and the maximum bias current, we calculated the maximum conversion gain for the discussed bolometric mixers. The maximum gain is the same for the discussed devices, as shown in Table IV. However, the optimal P_{LO} is reduced for smaller devices. Because at THz frequencies the output power of LO sources is low, reduction of the bolometer size to a submicrometer scale will be desirable.

The calculated conversion gain as a function of the bias current for a 3μm×1μm bolometer is plotted in Fig. 5 for the LO power of 0.038mW (red line) and 1.5 mW (blue line). The conversion gain, measured at 100 GHz for various LO power values, is shown by symbols. The measured points follow the theoretical curves very well. For the maximum available LO power of 0.74mW, the measured conversion gain was -28dB at 10mA bias current.

TABLE IV.
MAXIMUM CONVERSION GAIN, G_{mmax} CALCULATED FOR THE DISCUSSED BOLOMETERS. DEVICE PARAMETERS, WHICH WERE USED FOR THE CALCULATIONS, ARE ALSO GIVEN.

Size (μm^2)	2x1	3x1	4x1
G_{mmax} (dB)	-18.6	-16.9	-18.7
C_0 (Ω/mW)	2.6	1.6	0.5
i_{max} (mA)	8.2	11.4	18
R (Ω)	72	58	40
P_{LO} (mW)	4.8	7.5	13

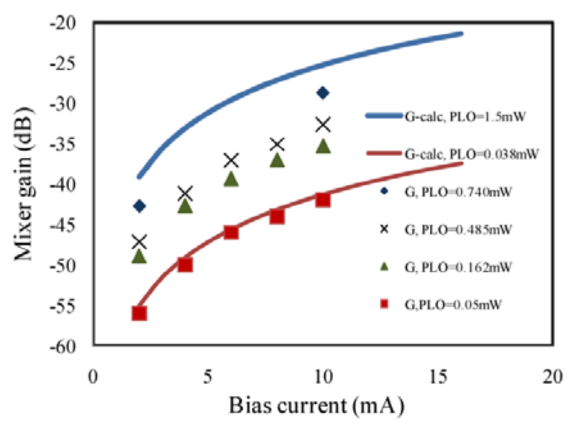

Fig. 5. Calculated (solid lines) and measured (scattered symbols) conversion gain for various LO power for a 3μm×1μm YBCO bolometer mixer at room temperature.

VIII. Response time

The bolometer response time is defined as a ratio of the bolometer heat capacitance, C to the thermal conductance into the heat sink, G:

$$\tau = C/G \quad (9)$$

Up to now, we discussed the bolometer operation in the quasi-stationary regime, i.e. when the RF signal modulation frequency $\omega << 1/\tau$, where τ is the bolometer time constant, or the response time. At an arbitrary modulation frequency, ω the bolometer responsivity is [14]:

$$R_V(\omega) = \frac{R_V(0)}{\sqrt{1+\omega^2\tau^2}} \quad (10)$$

where $R_V(0)$ is the responsivity at ω=0.

A faster response time allows for higher acquisition rates (e.g. for a greater frame rate in a THz camera). Using high modulation frequencies also helps to avoid the flicker noise of the readout electronics (which normally scales as $1/\omega$).

For a bolometric mixer, a faster response time means a larger gain bandwidth. The gain bandwidth is defined by a cut-off IF frequency, where the mixer gain rolls off by a factor of two of its value at zero frequency:

$$G_m(\omega_{IF}) = \frac{G_m(0)}{1+\omega_{IF}^2\tau^2} \quad (11)$$

Because both the heat capacitance and the thermal conductance are proportional to the bolometer area, the time constant does not depend on the bolometer area, but scales with the product of the YBCO specific heat, the film thickness, and the thermal boundary resistance (see (7) and (9)).

The specific heat of YBCO films at room temperature is approximately 400 J/kg×K (see e.g. [17]). Therefore, the response time can be calculated using (9) and results of the thermal conductance measurements from Section V. We obtain a time constant of approximately 2.2 ns.

The time constant can be also obtained by fitting the measured responsivity versus modulation frequency by (10), or the IF signal versus IF by (11).

We measured the voltage response of an YBCO microbolometer using a 90GHz active multiplier chain [18]. The input signal from an Agilent signal generator (15 GHz) was amplitude modulated in the range from 10Hz to 100kHz. In this frequency range, the bolometer response remained constant, with approximately 15% signal rise from 50 kHz to 100 kHz, which we currently cannot explain.

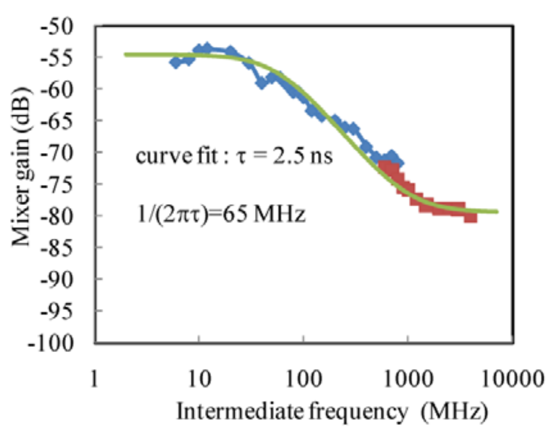

Fig. 6. Room temperature YBCO mixer signal versus IF (symbols), and a fitting curve corresponding to a response time of 2.5 ns (solid line). The corresponding mixer gain bandwidth is 65 MHz. Two microwave amplifiers were used in order to cover the IF range from 8MHz to 4 GHz.

In order to extend measurements to higher modulation frequencies, a mixing of two 90GHz sources was used. The sources were coupled to the mixer via a W-band 20dB directional coupler. A stronger source was used as the LO. The frequency of the other source (the signal) was tuned to provide an IF from 8MHz to 4GHz. The IF line width of a few MHz did not allow an IF lower than 8 MHz to be used. At each frequency point the signal source was amplitude modulated at a low frequency (20Hz) and the voltage response was measured using the lock-in amplifier. This signal was later used to calibrate for the power variation of the signal source during the frequency tuning. The result of the measurement is shown in Fig.6.

The measured G_m(IF) curve has double plateau shape, as it has already been reported for superconducting YBCO bolometers [19]. The lower frequency roll-off is associated with the thermal conductance through the film/substrate interface (often called a bolometric response). For the bolometric response, a reasonable fit to our measurements can be done using a 2.5 ns time constant. This response time corresponds to a 3dB gain roll-off at 65 MHz. Above 1 GHz, the mixer gain has a second plateau that has previously been associated with the non-equilibrium response of the YBCO film [19]. For an YBCO film at room temperature, the effect of the THz current is entirely thermal because there is no other mechanism to increase the film's resistance except the Joule heating. Therefore, the shape of the G_m(IF) curve will remain the same at higher RF frequencies. Our measurements on similar bolometers in the resistive state at 77K [11] showed that this is true for G_m(IF) recorded at both 90 GHz and 530 GHz.

IX. Noise

The noise voltage in the 4μm×1μm YBCO bolometer was measured from 20 Hz up to 100 kHz using the lock-in amplifier. The input noise of the lock-in amplifier was measured with a 50 Ω resistor connected instead of the bolometer and biased at 10mA (Fig.7, circles). The Johnson noise of the resistor at room temperature is 0.9 nV/Hz$^{0.5}$. Therefore, as it appears from Fig. 7, the readout noise is determined by the noise of the lock-in amplifier (3-4 nV/Hz$^{0.5}$) at and above 200 Hz. At lower frequencies, the *1/f* noise is dominating, probably originating from the dc bias current source.

Results of the bolometer noise measurements at 1mA, 3mA, and 15mA bias currents are shown in Fig.7 with crosses, diamonds, and triangles, respectively. The *1/f* noise is clearly visible at low frequencies. It scales approximately linearly with the bias current. At 15mA, the system noise is reduced to 5-6 nV/Hz$^{0.5}$ for frequencies above 5kHz, close to the noise of the lock-in amplifier. For a responsivity of 10V/W (corresponding to the 15 mA bias, Fig.4), the system noise equivalent power is calculated as *NEP*=600 pW/Hz$^{0.5}$. By subtracting the readout noise, the bolometer NEP is calculated as $((6\ \mathrm{nV/Hz^{0.5}})^2-(4\ \mathrm{nV/Hz^{0.5}})^2)^{0.5}/\ 10\ \mathrm{V/W}=$ 450 pW/Hz$^{0.5}$.

Using bolometer characteristics as discussed in the previous sections, the Johnson noise and the phonon noise can be calculated from (3) as 0.72 nV/Hz$^{0.5}$, and 0.33 nV/Hz$^{0.5}$, respectively. Therefore, for the 4μm×1μm YBCO bolometer the projected minimum NEP is 78 pW/Hz$^{0.5}$ for a bias current of 15 mA and modulation frequencies above the cut-off of the *1/f* noise. These results show that the measured NEP is limited by the readout and it can be further reduced using a preamplifier with a lower input noise. At the maximum bias of 26mA (see Section VII), an NEP of 43 pW/Hz$^{0.5}$ is expected for the discussed device, whereas an NEP of 24 pW/Hz$^{0.5}$ is expected for the 2μm×1μm bolometer.

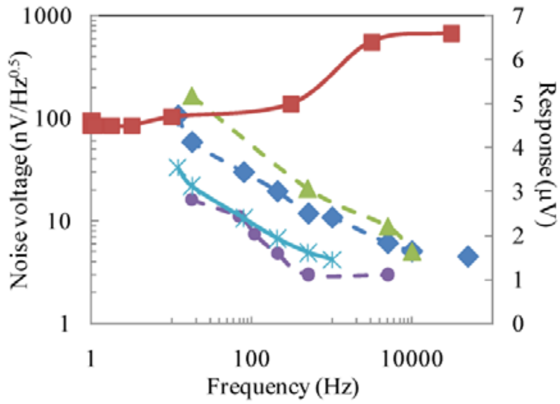

Fig. 7. Noise spectra of a 4μm×1μm YBCO bolometer at 1mA (crosses), 3mA (diamonds), and 15mA (triangles) bias current. Response spectrum (squares) is shown for a 3mA bias current. Circles show the noise of a biased (10mA) 50 Ohm resistor.

As we discussed in Section V, the responsivity scales inversely with the bolometer size. The bias current will be reduced proportionally to the bolometer width. The later fact might lead to a reduced low frequency noise. However, more research on the noise in nanometer size bolometers is needed.

Due to a low TCR of YBCO films at room temperature, the Johnson noise will also dominate over the phonon noise in YBCO mixers [15]. Therefore, the output noise of YBCO mixers at room temperature will be approximately 300 K (-174dBm/Hz). During our mixer tests, the system output noise (at 20 MHz) was measured to be approximately the same as with a 50 Ω load replacing the mixer at the IF amplifier input. It means that our estimate for the mixer IF noise is correct. With a -28dB conversion loss, the input noise is calculated to be -146 dBm/Hz.

X. Discussion and Conclusion

Thin YBCO films appear to be very promising for room temperature THz microbolometers. Made on a bulk substrate, bolometers demonstrate a response time of 2 ns (65MHz), which is approximately a factor of 100 smaller than for any other room temperature bolometers. Integrated with an antenna, the bolometer area can be made very small which reduces the bolometer thermal coupling to the substrate and, hence, increases the responsivity. For further optimization, the size of YBCO microbolometers has to be minimized. Inserting expression for the maximum bias current (8) in the equation for the responsivity (6), we obtain an equation for the bolometer maximum responsivity as a function of the bolometer parameters:

$$R_{vmax}= (0.6\, R_{bd}\cdot\alpha\cdot\rho\, /\, (w^2\cdot d))^{0.5} \qquad (12)$$

Using (12), a responsivity of 722 V/W can be calculated for a 0.1μm×0.1μm bolometer, which is quite feasible via modern e-beam lithography. The corresponding bias current is 0.59mA. Assuming the Johnson and the phonon noise sources to be dominating at high modulation frequencies, an NEP of 3 pW/Hz$^{0.5}$ is expected. Such optimization will not sacrifice the bolometer response rate, which is determined by the thermal boundary resistance, R_{bd}, and the film thickness, d. With regards to the film thickness, thinner films will probably have lower TCR, and hence will not bring any improvement of the responsivity. If the ratio $\alpha/\cdot d$ remains constant for thinner films, reduction of d could be beneficial for a shorter response time.

In Table V, we compare our bolometers with other room temperature bolometers [10], [20], with commercially available Schottky diode detectors [21], and MOSFET detectors [22]. As can be seen, the sensitivity of bolometric detectors approaches the one for Schottky diodes for frequencies at and in excess of 1THz. For submicrometer dimensions the thermal conductance in YBCO bolometers becomes much lower compared to the Nb- air bridge bolometers, providing a lower NEP and a much shorter (a factor of 1000) response time.

The RF bandwidth of the discussed YBCO bolometers is limited only by the antenna that can span over a few THz. Fabrication of the YBCO microbolometers is very straightforward and large bolometer arrays are quite feasible.

For heterodyne detection, YBCO bolometer mixers demonstrate a conversion gain of -28dB with a -3dB roll-off at 65MHz. For these devices (3μm×1μm) the maximum conversion gain is projected to be -17dB for a LO power of 7.5 mW. The input noise of the 3μm×1μm mixer is -146dBm/Hz, i.e. approximately 30dB lower, compared to the aforementioned MOSFET detectors in the heterodyne mode [22].

Using (8), the following equation for the optimal LO power can be obtained:

$$P_{LOopt}= 0.15\, w\cdot l\, /\, (R_{bd}\cdot\alpha) \qquad (13)$$

As seen from (13), the optimal LO power scales inversely with the bolometer size. For a 0.1μm×0.1μm bolometer, an optimal LO power is 24 μW, which can be obtained from solid state sources at least up to 2 THz [21], [23]. With the 24 μW LO power, submicrometer YBCO mixers are expected to provide approximately -18dB conversion gain, i.e. ~8000 K mixer noise temperature (DSB).This is close to the performance of Schottky diode mixers at 2.9THz with a 5mW LO power (obtainable only from a molecular gas laser or from a cooled quantum cascade laser) [24].

TABLE V.
COMPARISON OF ROOM TEMPERATURE THZ DETECTORS.

	TCR, %/K	G, μW/K	i_{max}, mA	R_v, V/W	NEP, pW/Hz$^{0.5}$	NEP, theory pW/Hz$^{0.5}$	τ, ns
Schottky diode detectors, 0.8-2THz [21]				100-400	100-20		0.001
MOSFET [22]					300		
bolometer Nb on SiO_2, [20]	0.2	22	5	15	50		200
bolometer Nb-air bridge, [10]	0.15	4	1.6	85	25		2000
bolometer YBCO, 2 μm ×1 μm, *this work*	0.26	53	11	at 11mA: 33 at 5mA: 12	370	36	2.5
bolometer YBCO, 0.1 μm × 0.1 μm, *projected*	0.26	0.37	0.59	722		3	2.5

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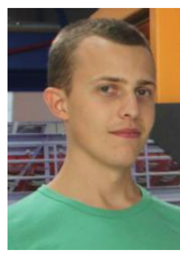
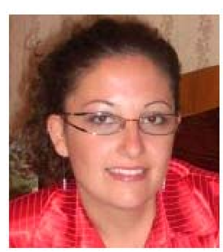
Sergey Cherednichenko, was born in Mariupol, Ukraine in 1970. He received the Diploma with Honours in Physics in 1993 from Taganrog State Pedagogical Institute, and Ph.D. in physics in 1999 from Moscow State Pedagogical University.
He is working at the Department of Microtechnology and Nanoscience at Chalmers University of Technology (Gothenburg, Sweden). From 2000-2006 he was involved in development of terahertz band superconducting mixers for the Herschel Space Observatory; and from 2008 till 2009 in the water vapour radiometer for ALMA. From 2007 he is Associate Professor at the department of Microtechnology and Nanoscience of Chalmers University of Technology. His research interests include terahertz heterodyne receivers and mixers, photon detectors; THz antennas and optics; thin superconducting films and their application for THz and photonics; and material properties at THz frequencies.



Arvid Hammar was born in Uddevalla, Sweden in 1986. He received the B.Sc. degree in 2008 from the department of Earth and Space Sciences at Chalmers University of Technology, Gothenburg, Sweden.
The thesis included measurements of the characteristic 21 cm line from H1 gas in the Milky Way and an evaluation of a minor radio telescope system at Onsala Space Observatory. In 2009 he was working at the Institute of High Energy Physics and Astrophysics at University of Florida where he was involved in various programming tasks for the CMS detector at CERN, mainly error analysis and particle trajectory simulations. Since 2010 he has been working as amanuensis at the Terahertz and Millimetre Wave Laboratory, Chalmers University of Technology, where he also currently is working towards the M.Sc. degree. The diploma work is about the development of high Tc hot electron bolometer based on thin YBCO films.



Stella Bevilacqua, was born in Pizza Armerina, Italy in 1981. She received B.Sc. degree in Electronic Engineering from the University of Catania, Italy, in 2006.
During a four months period, she has done her thesis work in the Smart-Card group of the MPG division of Catania STMicroelectronics. In April 2010, she received M.Sc. degree in Microelectronic Engineering from the University of Catania. She was a diploma worker at Chalmers University of Technology in the Department of Microtechnology and Nanoscience, where she was working towards her master thesis: 'Fabrication and

Characterization of Graphene field-effect transistors (GFETs)', for a six months period. Currently, she is a PhD student the department of Terahertz Millimeter Wave Laboratory of the Chalmers University of Technology, working on MgB2 Hot Electron Bolometers.

Vladimir Drakinskiy was born in Kurganinsk, Russia, in 1977. He received the Diploma degree in Physics and Informatics (with honors) from the Armavir State Pedagogical Institute, Armavir, Russia, in 2000.

From 2000 to 2003, he was with the Physics Department, Moscow State Pedagogical Univ., Russia, as a post-graduate student, junior research assistant. Since 2003 he has been with the Department of Microtechnology and Nanoscience of Chalmers University of Technology (Gothenburg, Sweden). In 2003-2005 he was responsible for mixer chips fabrication for the Herschel Space Observatory in 2003-2005. From 2008 he is Research Engineer at the department Microtechnology and Nanoscience of Chalmers University of Technology. His research interests include micro- and nanofabrication techniques, detectors for submillimetre and terahertz ranges and superconducting thin films.

Jan Stake (S'95–M'00–SM'06) was born in Uddevalla, Sweden in 1971. He received the degrees of M.Sc. in electrical engineering and Ph.D. in microwave electronics from Chalmers University of Technology, Göteborg, Sweden in 1994 and 1999, respectively.

In 1997 he was a research assistant at the University of Virginia, Charlottesville, USA. From 1999 to 2001, he was a Research Fellow in the millimetre wave group at the Rutherford Appleton Laboratory, UK, working on HBV diode multiplier circuits for submillimeter-wave signal generation. He then joined Saab Combitech Systems AB as a Senior System Consultant, where he worked as an RF/microwave engineer until 2003. From 2000 to 2006, he held different academic positions at Chalmers and was also Head of the Nanofabrication Laboratory at MC2 between 2003 and 2006. During the summer 2007, he was a visiting professor in the Submillimeter Wave Advanced Technology (SWAT) group at Caltech/JPL, Pasadena, USA. He is currently Professor and Head of the Terahertz and Millimetre Wave Laboratory at the department of Microtechnology and Nanoscience (MC2), Chalmers, Göteborg, Sweden. His research involves sources and detectors for terahertz frequencies, high frequency semiconductor devices, graphene electronics, terahertz techniques and applications. He is also co-founder of Wasa Millimeter Wave AB.

Alexey Kalabukhov was born in Moscow, Russia in 1975. He received his PhD degree in physics and mathematics from Moscow State University in 2003. His main research work is in design and fabrication of high-Tc SQUIDs for various applications including non-destructive evaluation and high-frequency amplifiers. In 2003, he joined the Quantum Device Physics group of the Microtechnology and Nanoscience department, Chalmers University of Technology. Recently, he has been working in the field of oxide electronics and functional oxide interfaces.