Wideband THz detectors based on YBCO thin films at 77K and at room temperature.

S. Cherednichenko, A. Hammar, S. Bevilacqua, V. Drakinskiy, J. Stake.
Terahertz and Millimetre Wave Laboratory, Chalmers University of Technology,
SE-412 96 Göteborg, Sweden

***Abstract*-We present results of experimental investigation of THz direct detectors based on ultrathin YBCO films. The detectors are integrated with a spiral planar antenna. In the frequency band of 0.1-1.6THz the optical responsivity is from 170V/W for 77K. It increases to 400 V/W for operation temperature about 76K. The responsivity was constant up to 100kHz. Using mixing technique, the measured time constant is ~0.5-2ns. Currently, at 77K, the NEP is ~20pW/Hz$^{0.5}$. At room temperature, the NEP is about 250pW/Hz$^{0.5}$. For the same devices as coherent detector, the mixer gain was -21dB at 77K (and -28dB) at room temperature for an LO power of 0.4mW. With the present devices a mixer gain of up to -23dB is possible at 300K for an LO power of 1.5mW. Using smaller devices, similar gain can be achieved for a much smaller LO power.**

I. Introduction

Low –Tc superconducting bolometers are extensively used both as direct detectors and mixers, where they show performance superior to other types of devices (for mixers at frequencies above 1THz) [1]. On contrast, semiconductor detectors require no cooling and hence are more convenient to use (no limits on the instrument operation time, smaller mass). The state of the art performance for room temperature direct detectors is 0.24 pW/Hz$^{0.5}$ at 95GHz for InAs/AlSb/GaSb backward diodes [2] and for zero biased Schottky diodes at 600-900GHz a NEP of about 5 to 20 pW/Hz$^{0.5}$ was reported [3]. Despite of extended research on bolometric photo detectors based on thin high-Tc superconducting YBCO films, there is a little information on their performance in the subMM range. Currently, very compact and lightweight cryocoolers to 77K are available, what facilitates the use of this type of detectors. Our goal was to fabricate and measure the responsivity and the noise of antenna integrated YBCO bolometers through the whole subMM range. Such bolometer were tested both for incoherent and coherent detection. Because of a rather large Temperature Coefficient of Resistance (TCR) of YBCO films in the normal state (i.e. at a temperature above 90K) such bolometers, as we discovered, provide also high sensitivity even in the normal state, well up the room temperature. Bolometers voltage responsivity and down conversion gain was measured at the room temperature at 100GHz and 500GHz.

The bolometers were fabricated of 50nm YBCO films made by pulsed laser deposition on r-cut Al_2O_3 substrates with a thin CeO_2 buffer layer. The bolometer length was about 1μm and the width varied from 1.5 to 4 μm. The bolometer was situated at the center of a logarithmic spiral antenna, which covers (based on our earlier findings) a frequency range from 300GHz to 2.5THz. The detector/antenna chip was mounted on a 12mm elliptical silicon lens (Figure 1). The critical temperature of the bolometers was about 86K and the cooling was arranged in a LN optical cryostat. A heater was used to bring the device to temperatures above 77K and LN vapor pumping was used to reduce the temperature. The bolometer was dc current biased to the resistive state (exceeding the critical current of 2-7mA, depending on the device).

Above 100K the dR/dT is approximately 0.2-0.4 Ω/K, for different device sizes. But the TCR is the same for all devices, which at room temperature is approximately 0.008 K^{-1}.

The voltage response from the bolometer was directly measured by a lock-in amplifier (at room temperature), with an input noise of 4-5 nV/Hz$^{0.5}$. For the mixer tests, the IF signal was preamplified with an room temperature LNA with a noise temperature ~100K.

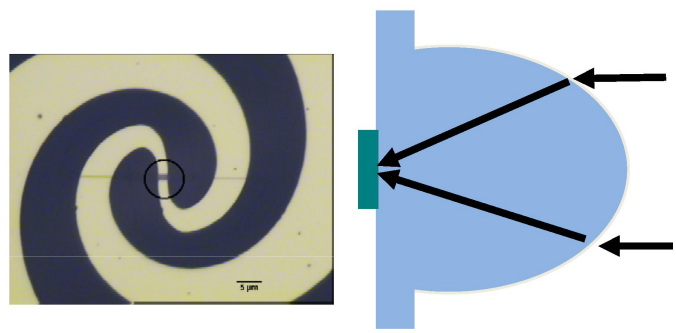

Figure 1. A photograph of a spiral antenna-integrated YBCO microbolometer.. The bolometer is in the circle. (left) The bolometer chip is mounted on an elliptical silicon lens. (right)

The responsivity was measured by the ratio of the output voltage to the input RF power. A W-band Gunn oscillator, a 300-550GHz BWO, and a FIR gas laser were used as the subMM signal sources. The source to the bolometer optical coupling was arranged via a Teflon lens (Figure 2). The power of the signal incident on the cryostat was measured by both the Thomas Keating (optical) and Erickson (waveguide with a horn) power meters. For the responsivity calculations, the incident RF power was calibrated for the cryostat window loss (0.7), and the spiral antenna to the linear polarization coupling loss (0.5). The circular polarization of the antenna was verified at 300GHz by measuring the bolometer response while rotating the bolometer block (at room temperature) around the optical axis. We shall note, that in order to ensure a single spatial

mode of the BWO beam, a WR10-WR3 waveguide transition and a WR3 smooth wall circular horn were connected to the output waveguide (WR10) of the BWO. By doing it, we limited the available RF power, however it makes the power calibration more reliable.

The noise voltage was measured with the same lock-in amplifier once the RF signal was blocked. The output IF noise of the bolometer was measured by comparing the system noise with the bolometer bias on and off. In the superconducting state the bolometer output noise was about 150K.

For the mixer tests at 530GHz two BWOs , one as an LO and the other as a signal source, were coupled via a thin film beam splitter. At the W-band (90GHz) there was more power available from the Gunn oscillator sources. Therefore, two Gunn sources were also used for the mixing tests, or (as in Figure 3), one Gunn oscillator and an active multiplier [4].

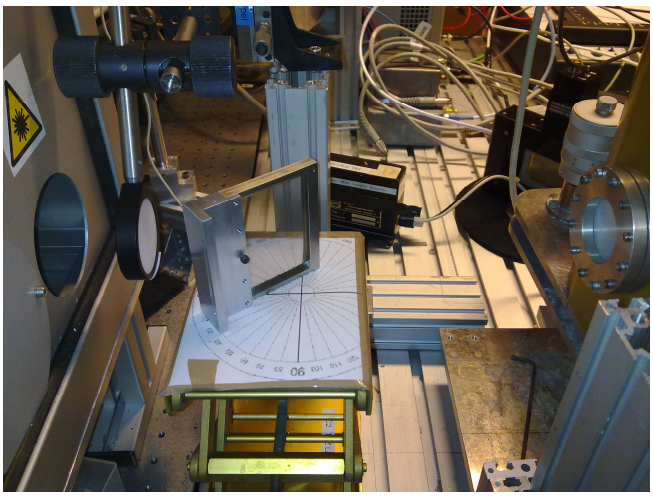

Figure 2. Direct detection test at 0.7 and 1.6THz with a FIR laser (left). The detector is in the cryostat on the right.

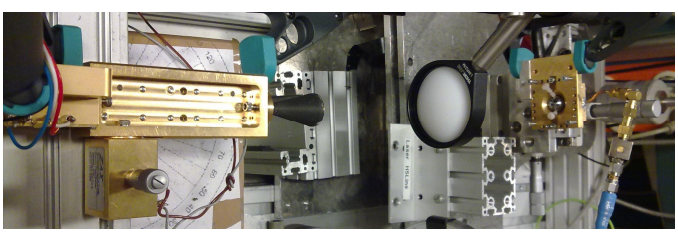

Figure 3. YBCO mixer test at room temperature. A W-band Gunn oscillator and a W-band active multiplier are coupled using a W-band directional coupler, to be used as a signal and an LO sources

We have found that in the superconducting state the responsivity scales reversely proportional to bolometer area. Such behavior is expected since the bolometer responsivity is

$$S_V = \frac{i \cdot \partial R/\partial T}{G - i^2 \cdot \partial R/\partial T} \qquad (1)$$

, where $G=w\times l/R_{bd}$ is the heat conductivity from the bolometer to the substrate, and R_{bd} is the YBCO/substrate boundary thermal resistance. For the smallest devices, 1.5x1μm^2 , the highest responsivity ~400kV/W is achieved at 76K, while it is about 170 V/W at 77K (see [5] for details). The responsivity was constant from nearly 100GHz up to 1.6 THz. By applying an amplitude modulated source signal to the active multiplier (90GHz output frequency [4]) we were able to measure the bolometer responsivity up to 100kHz (by the lock-in amplifier) and between 100kHz and 500kHz using a spectrum analyzer. No responsivity drop was observed. Higher responsivity requires higher bolometer electrical resistances, which was still not optimized. The noise was measured at 77K and was readout system limited to 4-5nV/Hz$^{0.5}$ for frequencies above 500Hz. It results in **NEP~20pW/Hz$^{0.5}$** .

In Figure 4, we summarize the NEP data for the 1.5x1μm^2 bolometer. Published NEP values for some semiconductor detectors are given also for comparison. Using a lower noise readout the NEP of the present devices can be reduced down to 2pW/Hz$^{0.5}$. Alternatively, the voltage responsivity of YBCO bolometers can be increased by reducing the bolometer area. In our lab we have an experience of fabricating 500×100nm bolometers, which theoretically shall have about a factor of 30 higher responsivity, hence lower NEP, compared to the devices from Figure 4. We expect that good superconducting properties can be preserved in YBCO bolometers as narrow as 50nm.

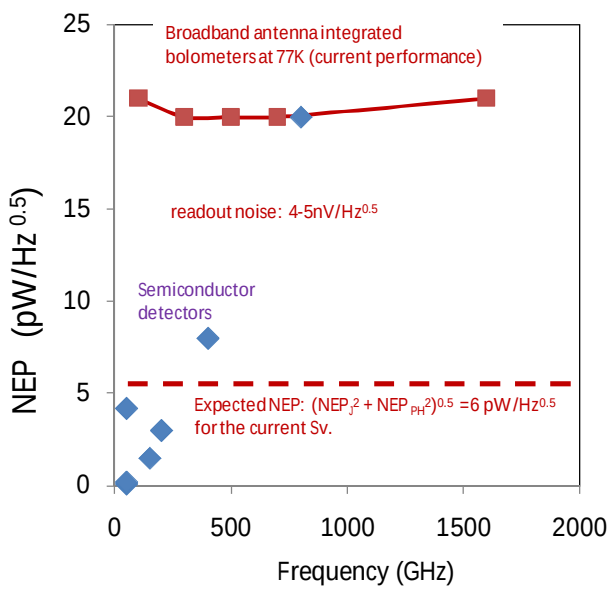

Figure 4. NEP versus signal frequency at 77 K for the 1.5 μm × 1.5 μm (diamonds) sized bolometers (squares). The dashed line is the bolometer NEP calculated from the Johnson and phonon noise contributions and the currently obtained Sv. Blue diamonds show the current performance of semiconductor detectors (e.g. Schottky diodes [2], [3]).

The conversion gain of the same bolometers was measured at 530GHz and 90GHz. The signal and the LO power was computed using the voltage responsivity, measured in the previous tests and the voltage swing corresponding to the RF (LO) on-off. For a 3 μm × 1 μm bolometer the maximum measured conversion gain was approximately -21dB for a 0.18mW LO power (530GHz). By reducing the bolometer temperature and simultaneously increasing the LO power, the

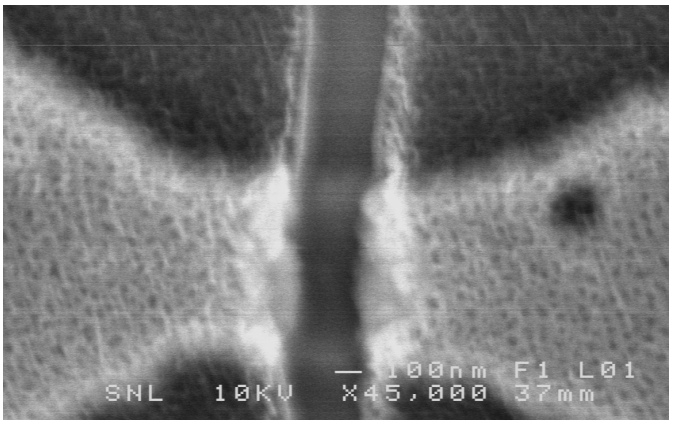

Figure 5. Scanning Electron Microscope image of an 500nm×100nm YBCO bolometer.

mixer gain will increase. If the pumped IV-curve is kept the same (i.e. a reduction of the temperature is compensated by an increase of the LO power), the mixer gain will change linearly with the LO power. Therefore, for a 2mW LO power a mixer gain of -11dB shall be possible to achieve for the discussed device.

It was very interesting to discover that our YBCO microbolometers have quite high sensitivity even in the normal state, in particularly at room temperature. The advantage of the room temperature operation over the superconducting state is the fact that $\partial R / \partial T$ is temperature independent, and, hence a large bias current can be applied. In the superconducting state, $\partial R / \partial T$ is determined by the resistive state in the bolometer, caused by the bias current. Therefore, in the superconducting state there is a bias current corresponding to a maximum responsivity. For the currents exceeding this optimum value, the responsivity decreases (see equation 1):

In the normal state, the responsivity is a linear function of the bias current. The limit here is the device breakdown. Our preliminary experimental data show that YBCO bolometers break when the current increases till the second term in the denominator in (1) approaches the first term. For safety reasons, we currently limit the bias current to about $i_{max} = (0.3\ G\ /\ \alpha\ R_1)^{0.5}$. Experimentally, a responsivity of approximately 15V/W has been achieved at room temperature. The system noise is still readout limited. Therefore, we estimate that at room temperature the NEP is approximately 250pW/Hz$^{0.5}$, for modulation frequencies 500Hz-100kHz.

Results for the mixer gain measurements at room temperature are given in Figure 6. For a bias current of 10mA and a LO power of 0.74mW (90GHz LO frequency), the measured mixer gain is -28dB. A gain of -21dB shall be reached for a bias current of 15mA and an LO power of 1.5mW. For smaller devices the LO power requirements are reduced. Our computations show that for a 500nm x 500nm bolometer a gain of -16dB shall be possible to achieve for a 0.5mW LO power.

In conclusion, at 77K YBCO thin film microbolometers

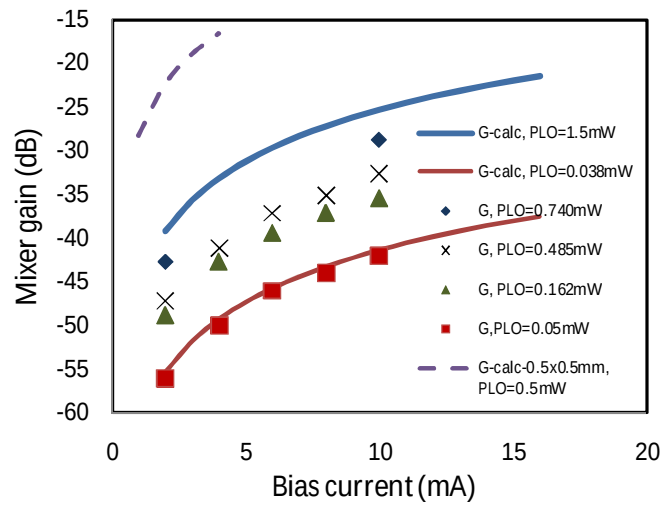

Figure 6. Measured (symbols) and calculated (solid lines) mixer gain for a 3μm×1μm bolometer at room temperature versus bias current. The used LO power is also given. The dashed line is the calculated mixer gain for a 0.5μm×0.5μm bolometer with a 0.5mW LO power.

show avoltage responsivity comparable to Schottky diode detectors for frequencies above 800GHz. The bolometer responsivity is nearly constant across a wide frequency range from 100GHz to 1.6THz, which is set by the antenna bandwidth. With a lower noise readout the bolometer NEP will reduce to about 6pW/Hz$^{0.5}$, which makes it the most sensitive THz detector without LHe cooling. Using smaller bolometers we expect to reduce the NEP by another order of magnitude. The same devices can be used both for incoherent and coherent detection. Intrinsically, there is no frequency limit for such detectors. Simplicity of the presented detectors makes the fabrication of large arrays quite straightforward.

REFERENCES

[1] S. Cherednichenko, V. Drakinskiy, T. Berg, P. Khosropanah, and E. Kollberg, Rev. Sci. Instrum., 79, 034501 (2008).

[2] N. Su, R. Rajavel, P. Deelman, J. N. Schulman, and P. Fay, "Sb-Heterostructure millimeter-wave detectors with reduced capacitance and noise equivalent power" *IEEE Electron Device Lett.*, vol. 23, no. 10, pp. 585–587, Oct. 2002

[3] L. Liu, J. L. Hesler, H. Xu, *Member*, A.W. Lichtenberger, and R. M. Weikle, "Broadband Quasi-Optical Terahertz Detector Utilizing a Zero Bias Schottky Diode," *IEEE Microwave WirelessComp.Lett.*, vol. 20, no. 9, pp. 504–506, Sept. 2010

[4] ALMA VWR LO source, Omnisys Instruments AB, Göteborg, Sweden.

[5] S. Cherednichenko, A. Hammar, S. Bevilacqua, V. Drakinskiy, J. Stake, "Terahertz direct detection in $YBa_2Cu_3O_7$ microbolometers," submitted to *IEEE Trans. Terahertz Technol.*,