Microwave Detectors Based on Granular High-T_c Thin Films

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Abstract —Detecting and mixing properties of microstrip superconducting Y–Ba–Cu–O and Bi–Ca–Sr–Cu–O thin-film structures deposited on various substrates have been investigated. The device performance was tested in 25, 55, and 110 GHz frequency bands at temperatures ranging from 100 K to about 50 K. Sensitivity obtained at 110 GHz was comparable to that of crystalline detectors. The mixing experiments were performed in a 25 GHz frequency band and indicated that the detector response time was less than 40 ps. The intermediate frequency was varied from 50 MHz to 5 GHz without any decrease in the mixer output up to 3 GHz. Auxiliary emission measurements performed at 12 GHz and down to 4.2 K revealed that the detector low-temperature performance limit was associated with microwave radiation from clusters of intergrain weak links arranged in multiloop quantum interferometers.

I. Introduction

CURRENT state-of-the-art in thin film technology of high T_c superconductors strongly suggests that in the near term the most successful applications of these materials will be in high-speed (microwave) electronics. It has been already demonstrated [1] that transmission lines patterned from an oriented high-T_c film can sustain the distortion-free propagation of electrical transients having a bandwidth of more than 100 GHz. On the other hand, only granular high-T_c superconductors have been so far implemented in active superconductive devices operational at liquid nitrogen temperatures. Granular films have been successfully tested as sensitive microwave and far-infrared detectors and mixers [2], [3].

Possible application of granular superconducting films for microwave detection has been the subject of intensive research in the past [4]. A comprehensive study of the microwave response of granular Sn films was published by Bertin and Rose [5] in 1971. The authors demonstrated the existence of a new nonequilibrium detection mechanism (enhanced mode of detection) in highly disordered films at temperatures below the superconducting transition temperature (T_c) and related it to the granular nature of the film. Other measurements, such as far-infrared video detection on NbN films, have also been reported [6]. Despite an excellent sensitivity and very low value of the noise equivalent power of enhanced-mode detectors [5], their practical applications were very limited, mainly due to their poor long-term stability and the requirement of liquid helium cooling.

In this paper we report on our studies of *granular* Y–Ba–Cu–O (YBCO) and Bi–Ca–Sr–Cu–O (BCSCO) detectors operational over the frequency range between 24 and 110 GHz at liquid nitrogen temperatures. We report also on mixing of two microwave signals in YBCO and BCSCO films. Performance of our detectors was very similar to that of the enhanced-mode detectors. However, a very complicated nature of ceramic superconductors manifested itself in the observed several new features, which cannot be accounted for by the simple model of a granular superconductor introduced by Bertin and Rose [5].

The paper is organized as follows: The next section describes our fabrication procedures for the depositing and patterning of granular YBCO and BCSCO films. An outline of the detector design and the experimental setup are presented in Section III. Sectiton IV displays the detecting properties of high-T_c films. Results of both video detection (demodulation) and heterodyne detection (mixing) experiments are reviewed. Section V discusses the possible physical mechanisms responsible for the detection process. Finally, conclusions are presented in Section VI.

II. Fabrication of YBCO and BCSCO Thin Films

In order to optimize the performance of the detectors, we fabricated high-T_c films of substantial granularity using either dc magnetron sputtering or chemical deposition from nitrate precursors [7], [8]. We have found that the properties of high-T_c ceramics depended strongly on the substrate material on which the deposition was performed. Several different substrates were tried: Al_2O_3, $LaAlO_3$, $LaGaO_3$, MgO, $SrTiO_3$, $ZrO_2+Y_2O_3$, and $ZrO_2+Gd_2O_3$. Although the first four of the above-listed materials show excellent dielectric properties at microwave frequencies, and we succeeded in growing superconducting films on all of them, as yet the best detectors were produced using ZrO_2, MgO, and sapphire substrates. For YBCO-on-ZrO_2, YBCO-on-Al_2O_3, and YBCO-on-MgO, the onset of superconductivity was 92 K, 90 K, and 85 K, respectively. In the case of the BCSCO film, besides the 80-K phase, a small

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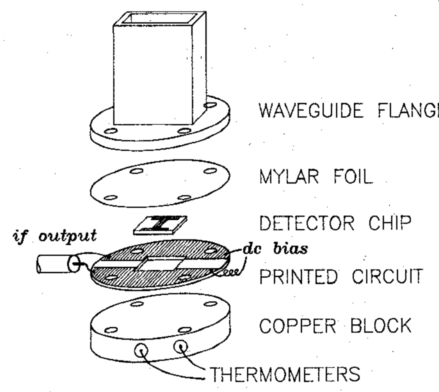

Fig. 1. Mounting structure of the high-T_c microwave detector.

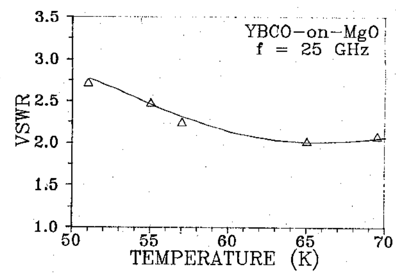

Fig. 2. Low-power VSWR dependence on temperature for the YBCO-on-MgO detector.

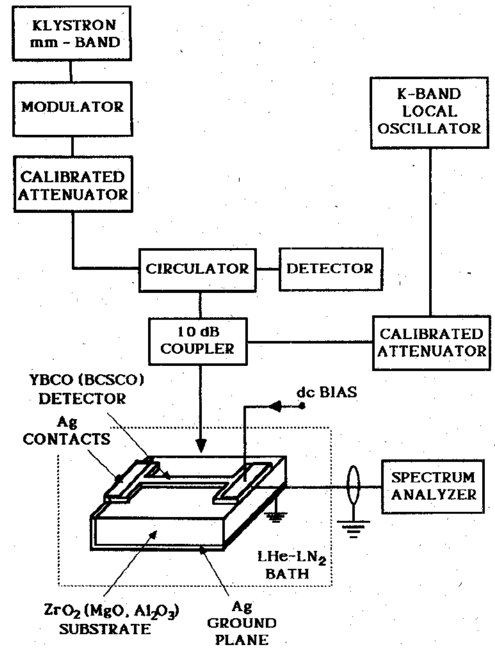

Fig. 3. Block diagram of the experimental setup.

percentage of the 110-K phase was also present. The BCSCO films were fully superconducting below 77 K.

Special post-deposition heat treatment was always necessary in order to obtain the granularity and transport critical currents appropriate for attaining good detection characteristics. The heat treatment (described in detail in [7] and [8]) was to some extent more critical than the type of deposition process used. Both magnetron sputtered and spray-deposited films were found useful when the prescribed annealing procedure was correctly applied. Magnetron-deposited films were more resistant to aging and showed better reproducibility. The advantage of sprayed films was that they could be easily patterned by the application of metallic stencil masks during the deposition process [8]. For complicated structures, a standard photolithographical process followed by wet chemical etching has been successfully implemented on both types of films.

III. Experimental Arrangement

A. Detector Design

Samples for our experiments were prepared in the form of superconducting microstriplines, which simultaneously served as an intermediate frequency (IF) and/or video output lines. After the deposition of the high-T_c strip, the entire back surface of the substrate was silver coated in vacuum to form a ground plane. Next, silver contact pads were deposited on both ends of the strip, with one of the pads extended over the substrate edge to make a short circuit with the ground plane, and the other patterned into a filter structure for the fundamental mode at the carrier frequency.

A simplified drawing of the mounting structure of our microwave receiver is shown in Fig. 1. The above-described detector chip is incorporated into a window cut in a wafer made of a microwave copper-clad reinforced-teflon laminate and it is sandwiched in between a copper heat sink and a special flange of the waveguide. Finally, a mylar washer is used to insulate the microstrip video/IF output line, and to set an appropriate capacitance of the filter.

There are some well-known difficulties in obtaining a proper impedance match between a superconducting film and a waveguide. Matching can be achieved by the proper choice of the strip width and, possibly, by using a waveguide of reduced height. Thickness of the dielectric substrate is also important, and its optimal value is frequency dependent. In addition, matching is temperature sensitive and current-bias dependent, though for high-T_c films, both these effects turned out to have a negligible effect on VSWR. In our case it was found that the strips 80–300 μm wide, with an active length of 2–3 mm deposited on 0.5–0.7 mm thick MgO substrates, could be matched with a VSWR of less than 2.5. This is illustrated in Fig. 2, where the VSWR of the YBCO-on-MgO detector is plotted as a function of temperature. The measured VSWR exhibited a shallow minimum and was constant for low applied microwave powers (shown, for example, in Fig. 4). A slight improvement was observed with the increase of the microwave power.

B. Experimental Setup

Our experimental apparatus, schematically presented in Fig. 3, consisted of millimeter-wavelength klystron sources (OKI: 24V11, 55V11, and 100V11) followed by a ferrite modulator, calibrated attenuator, circulator, and power-level monitor. For mixing experiments, a separate local oscillator channel was added. The microwave signal was delivered to our detectors through a rectangular R220 (WR-42) waveguide (not shown in the figure). In the case

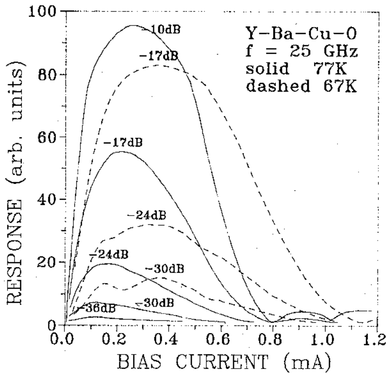

Fig. 4. Video response of the YBCO-on-ZrO_2 detector versus bias current for different 25 GHz signal power levels at 77 K and 67 K.

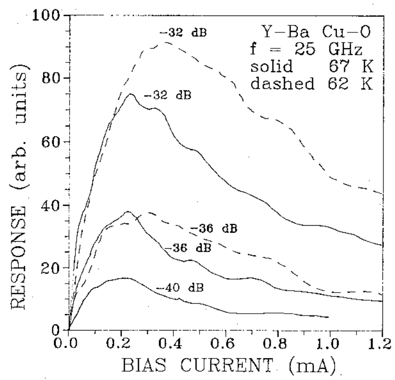

Fig. 5. Video response of the YBCO-on-MgO detector versus bias current for different 25 GHz signal power levels at 67 K and 62 K.

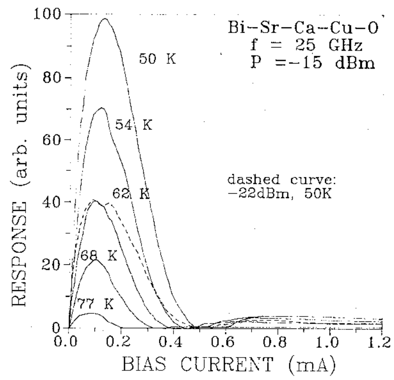

Fig. 6. Sensitivity of the video response of the BCSCO-on-MgO detector versus bias current for a sequence of operating temperatures. Microwave frequency was 25 GHz.

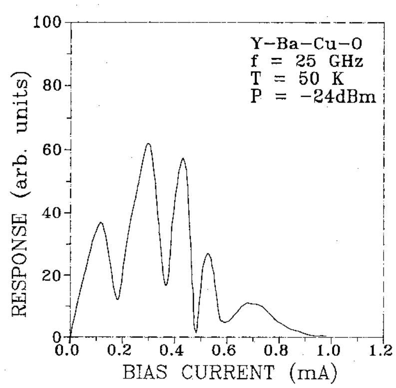

Fig. 7. Video response of the YBCO-on-ZrO_2 detector at 50 K (the same sample as shown in Fig. 4).

of measurements at 55 GHz and 110 GHz frequencies, a taper transition between R740 (WR-12) and R220 was applied. The video/IF detector output was connected to the signal-processing electronics via a semi-rigid coaxial cable. We used a low-noise selective nanovoltmeter for the video detection experiments. As it is shown in Fig. 3, a spectrum analyzer was used for direct IF detection.

The assembled detector was mounted inside a temperature-controlled cryostat. The device was supplied by controlled dc current bias and, if necessary, its current–voltage ($I-V$) and resistance–temperature ($R-T$) characteristics could be monitored during the same experimental run. All measurements were performed inside an electromagnetically shielded room.

IV. Detecting Properties of YBCO and BCSCO Films

A. Demodulation Experiments

In Figs. 4, 5, and 6 we show the response of YBCO-on-ZrO_2, YBCO-on-MgO, and BCSCO-on-MgO detectors, respectively, to a 1-kHz-amplitude-modulated 25 GHz signal. In some experiments, a 20-kHz-modulation frequency was used, and no difference between a 1- and 20-kHz response was observed. For comparison purposes, the devices chosen for presentation in Figs. 4, 5, and 6, while composed of different materials, had similar critical currents at 77 K. Thus the observed differences in the response curves we ascribe to different dielectric properties of the substrates. We have found that the sharpness of the superconductive transition was not of primary importance for our applications. In fact, the best detector performance was usually obtained below T_c and on the resistive "tail" of the $R-T$ curve.

All detectors exhibited a remarkable sensitivity increase at temperatures below 77 K. The BCSCO-on-MgO detector exhibited more than a 20 dB increase in sensitivity when it was cooled down to about 50 K. A similar though smaller sensitivity increase was noted for the YBCO-on-ZrO_2 and YBCO-on-MgO detectors. In the latter case, however, the decrease of the temperature below 65 K rendered the detecting properties sensitive to bias current in a complicated manner. Such features are shown in Fig. 7 for the same sample as in Fig. 4, but cooled to 50 K.

At 55 and 110 GHz we observed no new features. At 110 GHz the best results (Fig. 8) were obtained for YBCO deposited on sapphire. Note the proportionality of the detected voltage to the incident 110 GHz power. The sensitivity increase upon cooling down from 77 K to about 55 K was about 13 dB. Interestingly, at this latter temperature a total sensitivity of this particular, not perfectly optimized receiver was only about 6 dB worse than the sensitivity of the video receiver equipped with a commercial 1N53 crystal detector. We expect that a further refinement in the high-T_c receiver design should make it, at least at millimeter wavelengths, fully competitive with receivers based on crystalline detectors.

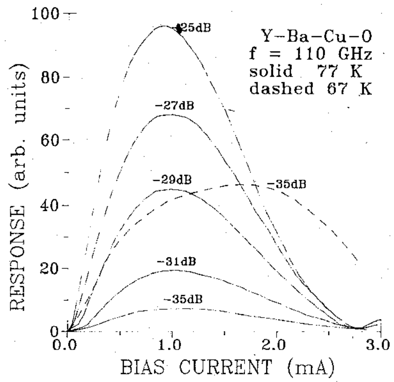

Fig. 8. Video response of the YBCO-on-sapphire detector versus bias current for different 110 GHz signal power levels at 77 K and 67 K.

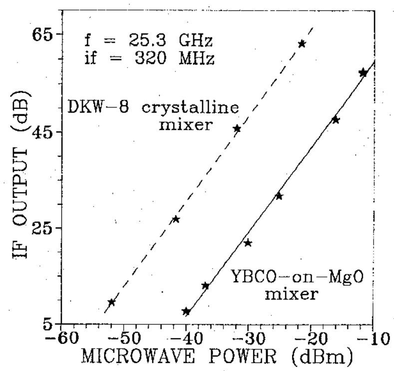

Fig. 9. Intermediate frequency output versus microwave signal input for the YBCO-on-MgO detector. The response of the DKW-8 microwave detector is shown for comparison.

B. Mixing Experiments

Mixing experiments were performed in the 25 GHz frequency range, and the results obtained for YBCO-on-MgO and BCSCO-on-MgO detectors were quite similar to those earlier reported for detectors on Al_2O_3 and ZrO_2 substrates [2]. YBCO mixer output was linear at the signal levels from -10 to -50 dBm (see Fig. 9). The local oscillator power was not very critical and exhibited a flat optimum level of the order of few mW. Similarly to the previously reported data [2], the optimum bias condition was around zero. The mixing action disappeared at about 80 K. By tuning both signal and local oscillator microwave sources, we were able to obtain IF frequencies from 50 MHz to 5 GHz. The IF level was almost constant for the frequencies up to 3 GHz. Further frequency increase deteriorated the output. However, this deterioration was caused by the sensitivity decrease of our spectrum analyzer, accompanied by an increased attenuation of the IF output line.

Observed coherent, heterodyne detection at 25 GHz implies that the detector response time is shorter than 40 ps, strongly suggesting that the nonlinear response is due to a network of Josephson-type weak-links present in our granular films. This type of interaction is intrinsically very fast because the corresponding maximum frequency should be only limited by the superconducting energy gap.

The BCSCO mixer performed similarly; however, its operating temperatures were substantially lower (mixing action disappeared around 60 K).

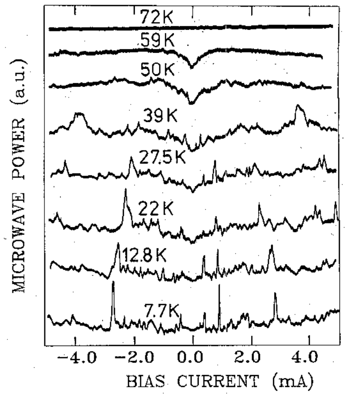

Fig. 10. Wide-band microwave emission ($f = 12$ GHz, $B = 250$ MHz) from current biased YBCO-on-ZrO_2 film at different temperatures. Successive curves are shifted for clarity.

V. Discussion

The physical processes responsible for the observed detection and mixing effects are a complicated mixture of known—and perhaps some unknown—mechanisms, appropriately enough for the complicated nature of the investigated system, which is a collection of superconducting grains interconnected by grain-boundary Josephson junctions and the normal nonsuperconducting phase. Nevertheless, the general behavior of our detectors is quite similar to the enhanced mode of detection, briefly discussed in Section I (see also [4]–[6]). The most characteristic feature is a substantial increase of the total sensitivity of our video-detectors at the temperatures far below T_c. Also, the short response time of the high-T_c detectors seems to rule out classical bolometric effects, though proportionality of the detected voltage to the incident microwave power is typical for a simple heating mechanism.

Some of us have proved the existence of Josephson weak links in the high-T_c granular films by detecting microwave radiation emanating from these films [9]. A typical example of radiation from YBCO film deposited on yttrium stabilized zirconia, as recorded by a 12 GHz superheterodyne receiver of 250 MHz bandwidth, is shown in Fig. 10. Such noise, clearly visible at liquid helium temperatures, decreases with the temperature increase and vanishes at liquid nitrogen temperatures. This is consistent with the Josephson coupling energy becoming smaller than the energy of thermal fluctuations, and leading to a vanishingly small supercurrent flowing across the sample.

The measured dc $I-V$ characteristics of our films (Fig. 11) were highly nonlinear up to T_c, and the film critical currents were clearly measurable at low temperatures. As it can be seen in Fig. 11 (see also [10]), the applied microwave power directly influenced the $I-V$ characteristics in a manner resembling the effects observed in microwave irradiated imperfect Josephson junctions [11]. Finally, the optimum bias required to maximize the sensitivity of video detection always corresponded to the region of highest $I-V$ nonlinearity.

Surprisingly, the efficiency of mixing exhibited a flat maximum at the zero bias and was substantially reduced at bias currents optimal for video detection. Apparently, the

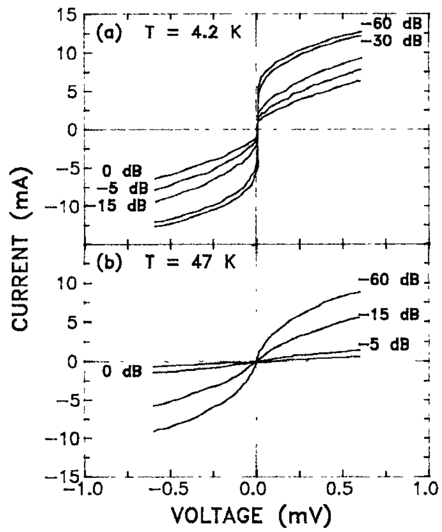

Fig. 11. $I-V$ charcteristics recorded for an YBCO-on-Al_2O_3 film irradiated by microwaves: (a) $T = 4.2$ K, and (b) $T = 47$ K.

mechanisms involved in mixing and in video detection are different, and new experiments (e.g., harmonic mixing) are necessary to shed light on this problem.

One should finally mention that the existence of the normal phase distributed between superconducting grains in our films can lead in the presence of microwaves to the creation of a dense network of hot spots of very small total volume and disturb the dynamical equilibrium of the system. The relaxation times involved in such processes can be of the order of 1 ps at 4 K [6], and at 77 K could be much shorter.

VI. Conclusions

In conclusion, high-T_c granular thin films offer interesting possibilities both as coherent- and video-detectors of millimeter waves. The lack of complete understanding of relevant physical mechanisms makes the device optimalization a difficult and challenging research problem. The best performance of our detectors was so far obtained at temperatures in the vicinity of 60 K, but the use of higher T_c superconductors (e.g., Tl–Ba–Ca–Cu–O or Bi(Pb)–Ca–Sr–Cu–O) should allow to obtain an efficient detection at 77 K.

We must emphasize that, while detection sensitivity increases with the temperature decrease, there is a physical limit on the detector's lowest-usable temperature (typically about 50 K). In highly granular narrow strips the limiting factor is the number of percolation paths available in the strip. Quasi one-dimensional transport at low temperatures manifests itself in quantum effects associated with clusters of intergrain weak links arranged in multiloop interferometers. As a result, the detector response is strongly bias dependent (see, for example, Fig. 8) and sensitive to the magnetic field. The excess noise generated in this manner was measured to be about 4×10^{-16} W(Hz)$^{-1/2}$ at 4.2 K [9].

Finally, one should consider the high-frequency limit of the proposed devices. Theoretically, it should be determined by the superconductor energy gap and fall in the terahertz range. However, our preliminary experiments [12] indicate that the video response falls off by one order of magnitude for the carrier frequency in the range between 100 and 300 GHz.

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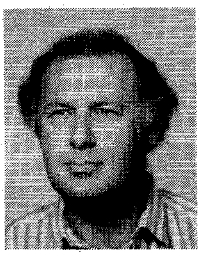

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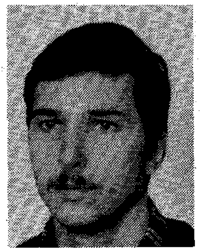

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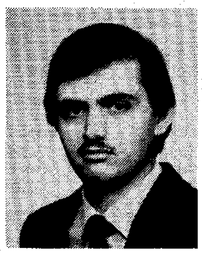

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