9.6 μm wavelength mixing in a patterned $YBa_2Cu_3O_{7-\delta}$ thin film

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Abstract

Hot-electron bolometric (HEB) mixing of 9.6 μm infrared radiation from two lasers in high-quality $YBa_2Cu_3O_{7-\delta}$ (YBCO) patterned thin film has been demonstrated. A heterodyne measurement showed an intermediate frequency (IF) bandwidth of 18 GHz, limited by our measurement system. An intrinsic limit of 100 GHz is predicted. Between 0.1 and 1 GHz intermediate frequency, temperature fluctuations with an equivalent output noise temperature T_{fl} up to ~150 K, contributed to the mixer noise while Johnson noise dominated above 1 GHz. The overall conversion loss at 77 K at low intermediate frequencies was measured to be ~25 dB, of which 13 dB was due to the coupling loss. The HEB mixer is very promising for use in heterodyne receivers within the whole infrared range.

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There is an increasing interest in wideband mixing in the far infrared range. A low bandgap semiconductor material, HgCdTe, as well as a GaAs multiple quantum well (MQW) structure have been used at 77 K in order to make direct, or incoherent, detectors in the technologically important infrared wavelength range 8 – 12 μm [1, 2]. As a coherent receiver, the sensitivity of the MQW detector is comparable to that of HgCdTe detectors, however the MQW has higher intrinsic speed. Their intermediate frequency (IF) bandwidth is usually less than 10 GHz. Recently, mixing of radiation from two CO_2 lasers using $YBa_2Cu_3O_{7-\delta}$ (YBCO) step-edge Josephson junctions [3] was demonstrated. In that work, two distinct mixing mechanisms were identified; hot-electron mixing in the junction banks at high dc bias, and Josephson mixing at low dc bias. In contrast to Josephson devices, a hot-electron mixer has an almost unlimited spectral range. The IF bandwidth, i.e. the difference frequency at which the hot-electron response rolls off, is determined by the electron-phonon energy relaxation time. Hot-electron mixing has been investigated in Nb [4-6] and NbN [7-9] films. Coherent detection with at least 18 GHz bandwidth using electron heating in a high-quality YBCO film has recently been demonstrated at 1.56 μm [10].

In the present work, we have used high-quality epitaxial YBCO films for mixing of 9.6 μm laser radiation. We demonstrate an IF bandwidth of 18 GHz, the highest reported to our knowledge, for a 10 μm-range heterodyne mixer. The bandwidth is at present limited by our post-detection instrumentation and our sample mounting technique. A model based on electron heating predicts an intrinsic bandwidth in excess of 100 GHz for a hot-electron bolometer (HEB) mixer.

A 50 nm thick YBCO film was laser deposited on $LaAlO_3$. By the use of photolithography, a mixer structure for infrared radiation, consisting of ten parallel strips, each ~1 μm wide was patterned in the film. The size of the mixer structure was 20×20 μm^2. A detailed description of the fabrication is given elsewhere [11]. Measurements were made using a temperature controlled closed-cycle helium refrigerator. The sample was attached with silver paste to a copper mount with the film surface up. One end of the mixer was wire bonded to the ground plane, while the other was connected to a 50 Ω microstrip line on alumina. The other end of the stripline was soldered to a semi-rigid 50 Ω coaxial cable. The laser radiation was focused on the active region of the sample with a lens placed outside of a window in our cryostat.

A cw grating-tuned CO_2 laser was used as local oscillator (LO) and a cooled PbSnTe tunable diode laser (TDL) was used as the signal source for our mixing experiment at 9.6 µm (see Fig. 1). The TDL operates at temperatures less than 80 K, and emits a single mode in the 9.4–9.6 µm wavelength range. By changing the drive current, the wavelength can be fine tuned in a small range, until a mode hop to another range occurs. Using the monochromator, it was possible to simultaneously study the emission spectra from both the TDL and CO_2 lasers. By selecting one particular of many possible lasing wavelengths from the CO_2 laser and carefully tuning temperature and the drive current for the TDL, a regime was found where the difference frequency of the two lasers could be tuned from zero to above 18 GHz by adjusting only the TDL drive current. The beams from the TDL and CO_2 lasers were combined in a beamsplitter and focused on the YBCO mixer structure. The signal power of the selected TDL mode was ~100 µW, while the incident CO_2 LO laser power was ~10 mW. The mixer was current biased to the resistive state at a point which gave maximum response and the signal was amplified and detected with a spectrum analyzer.

Figure 2 shows typical dc current-voltage (I–V) characteristics for the device with optimum bias range (marked with an oval for one of the curves). A minimum conversion loss for the mixer at T=77 K was achieved for the maximum LO power level of 17 dBm and a bias voltage of 300 mV. The LO power was measured before the focusing lens outside the cryostat. The coupling loss from this point to the mixer element was 13 dB. The maximum LO power level was limited by the capability of our laser system and the coupling loss. Therefore, we were not able to pump the device with enough LO power at T<77 K. The IF dependent response in the optimal operating point of the mixer is shown in Fig. 3 (open squares). The high-frequency ($f_{IF} > 3$GHz) conversion losses were measured to ~83 dB, including the coupling loss. The losses are much smaller at low intermediate frequencies, reaching ~25 dB at nearly zero IF. The latter value was found by plotting two I-V characteristics (under optimal LO power, P_{LO}, and $P_{LO}+\Delta P_{LO}$, respectively). The corresponding change of voltage across the 50 Ω load, ΔU, in the optimal mixing point was measured and the dc conversion loss was calculated as $\Delta P_{LO} \times (50\ \Omega)/(\Delta U)^2$. Figure 3 also shows two curves obtained at lower LO power levels. The data obtained in Ref. 10 for a similar sample at λ=1.56 µm with low LO power is presented as well (arbitrarily shifted vertically in Fig. 3). We note that all frequency spectra at λ=9.6 μm have a shape similar to the spectrum at λ=1.56 μm. This shows that the same bolometric mixing mechanism is present in both the near- and far-infrared spectral ranges. The data shows that the mixer signal is fairly flat between 4 and 18 GHz at both wavelengths. The different parts of frequency spectra like those in Fig. 3 have been discussed in detail previously [12].

Figure 4 shows the conversion gain dependence on LO power at two different intermediate frequencies (f_{IF}=20 MHz and 6 GHz). At each point the bias voltage was adjusted to maximize the signal. Whereas at f_{IF}=20 MHz the bias could be adjusted so the response reached an absolute maximum within the range of available LO power, the conversion gain at f_{IF}=6 GHz tends only to rise with increased LO power. This can be explained by the difference between the thermal conductivities for low-frequency and high-frequency IF signals. The effective thermal conductivity at 6 GHz (from electrons to phonons) is high and it is determined by the electron-phonon relaxation time. This requires the application of more LO power in order to obtain a maximum of the IF response. At low intermediate frequency (20 MHz), the thermal conductivity is mostly governed by the thermal boundary resistance at the film/substrate interface and is as much as 40 times lower than that at 6 GHz [13]. Consequently, it is much easier to reach the maximum IF response, since less LO power is needed.

We did not observe any manifestation of the Josephson mixing mechanism in our high-quality films, and believe that the frequency conversion is associated with modulation of nonequilibrium excitations of quasiparticles in the YBCO film. The effective relaxation time is of the same order of magnitude as that of the electron-phonon interaction, $\tau_{e\text{-}ph}$, which has been estimated to 1-2 ps at 80 K [12, 14]. A 1.5-ps photoresponse signal from a YBCO film attributed to the kinetic inductance mechanism was recently measured by the use of electro-optic sampling [15]. The above experiments clearly imply that the IF bandwidth of the HEB mixer is ~100 GHz.

Since the measured IF spectra in this work are very similar to those in Ref. 10, obtained at λ=1.56 μm, we believe that the ways to improve the conversion gain are the same. In particular, a substrate with high thermal conductivity (e.g. sapphire or silicon) would be useful to decrease the loss below 10 MHz. Theoretically, for 50 nm thick YBCO the difference in the conversion loss between intermediate frequencies in the dc and gigahertz regions can be as low as 30 dB [10, 13]. For thinner films (thickness 10 nm) this difference is 15 dB. Ref. 13 predicts the conversion loss limit at f_{IF}> 5 GHz to be approximately 6 dB. However, to reach this value a considerable technological effort is needed in order to improve both the film and substrate parameters.

The mixer output noise temperature, T_{out}, was measured by connecting a spectrum analyzer to the mixer IF port via a broadband amplifier with 200 K noise temperature. Noise levels were measured both when the mixer was biased at the point for maximum response and in the normal state at a temperature well above T_c. By comparing the levels, the mixer output noise temperature could be determined in the same manner as in Ref. 16. The output noise is assumed to consist mainly of temperature fluctuation noise (T_{fl}) and Johnson noise (T_J), i.e. $T_{out}=T_{fl} + T_J$. At λ=9.6 μm the radiation is uniformly absorbed ($\nu > 2\Delta/h$), the electrons have an equivalent temperature $\theta=T_c$, and T_J is approximately given by T_c. The output noise was measured in the frequency range 200 MHz to 2 GHz at T=77 K (see Fig. 3). The temperature fluctuation noise contributes significantly for f_{IF} <1 GHz at the optimum operating point, giving T_{fl} up to 150 K at the low-frequency end of the range. This type of noise should have the same frequency dependence as the IF signal.

The noise temperature limit for an MQW detector at 77 K, 10 μm wavelength, f_{IF}=1.5 GHz and P_{LO} up to 10 mW is as high as ~40,000 K [1]. This value is approximately 10 times larger than that of the best HgCdTe mixers at 77 K, λ_{LO}=10.6 μm and f_{IF}=1.5 GHz [17]. The single sideband (SSB) mixer noise temperature of our mixer prototype is still very high because of the large conversion loss. However, the output noise temperature fits well with bolometer noise theory, implying that the mixer sensitivity will be much improved when the conversion loss is reduced. The SSB noise temperature has been calculated for a device made from a 10 nm thick YBCO film on an infinitely thermal conductive substrate [13]. The total contribution of thermal fluctuation and Johnson noise at f_{IF}=2.5 GHz was found to be less than 2,000 K.

In conclusion, we have demonstrated 9.6 μm wavelength mixing in a high-quality YBCO thin film. We have examined a superconducting HEB mixer, consisting of narrow YBCO strips, biased into the resistive state. The device is incorporated into a transmission line, and can be realized with a technology which is relatively uncomplicated compared to the planar semiconductor fabrication. However, so far the reproducibility is higher in the more mature semiconductor fabrication technology. Our experiments at λ=9.6 μm show very promising results, with a measured total conversion loss of 25 dB at low frequency and an IF bandwidth of at least 18 GHz at 77 K. By optimizing the substrate material and the element size, the intrinsic conversion loss at high IF can probably be reduced to below 10 dB. The output noise is attributed to temperature fluctuations and Johnson mechanisms, implying that the mixer noise temperature limit is at a very low level. Furthermore, the device is well suited for integration with planar antennas in order to reduce the rf coupling losses. The performance of an optimized device can yield a sensitivity-bandwidth product that by far exceeds what is achieved with the best HgCdTe photodiodes. Based on the wavelength-insensitive nature of the superconductor electromagnetic interaction, our results could possibly be extrapolated to terahertz frequencies. Such a mixer would be very useful for high resolution spectroscopy and remote sensing in the 10–100 μm wavelength range.

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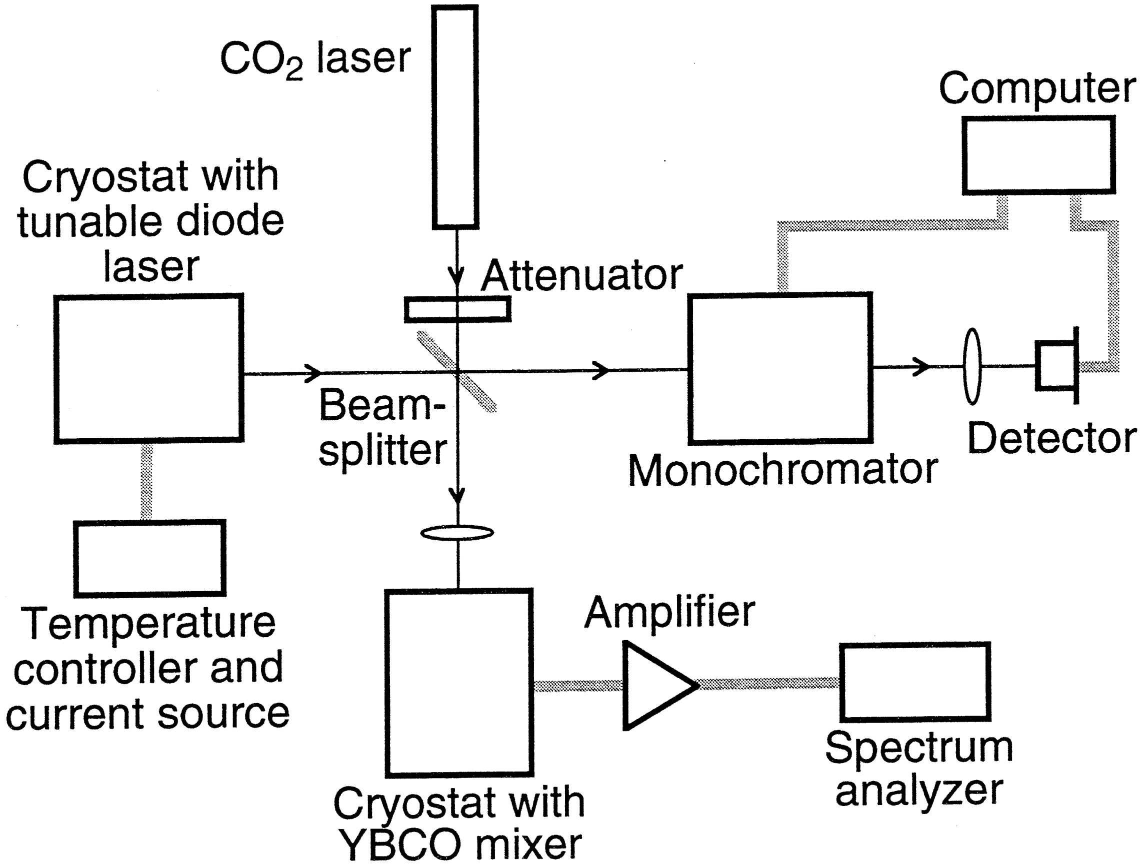

Fig. 1.Schematic view of the experimental setup

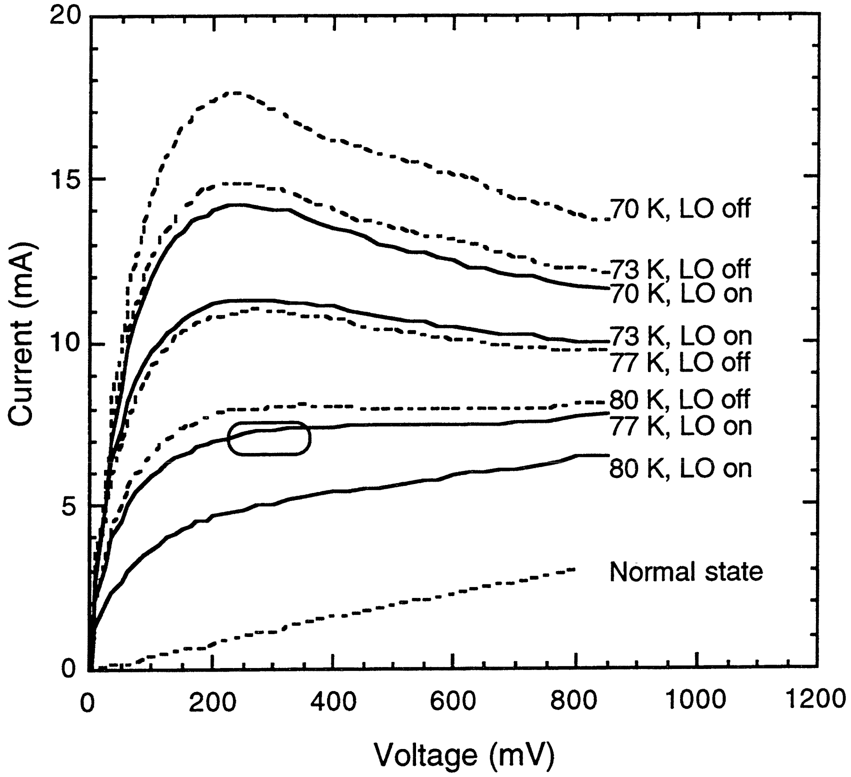

Fig. 2. Measured dc I-V characteristics with and without applied local oscillator (LO) power. The oval marks the bias range for optimum performance for one of the curve.

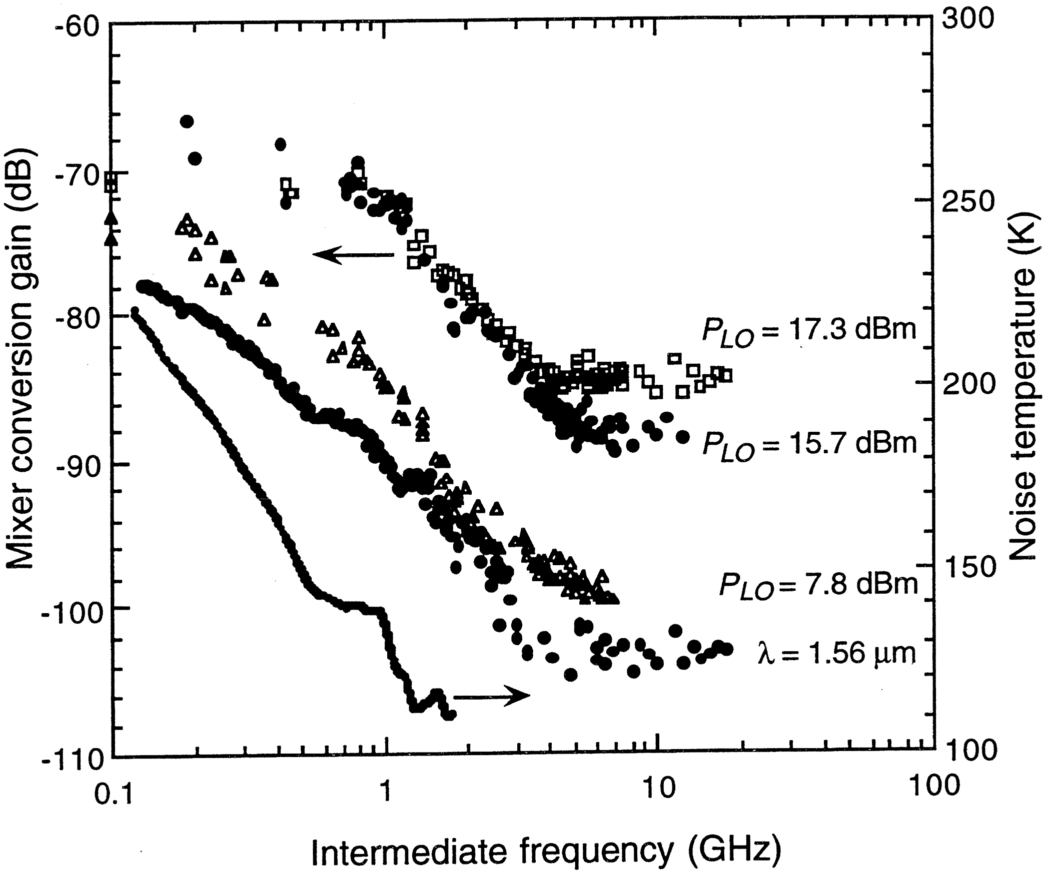

Fig. 3. Mixer response as a function of intermediate frequency (IF), measured both at λ=9.6 μm (three upper curves) and λ=1.56 μm (arbitrarily shifted vertically) [10]. The lower curve is the measured mixer output noise temperature. A 13 dB coupling loss is included in the 9.6 μm data.

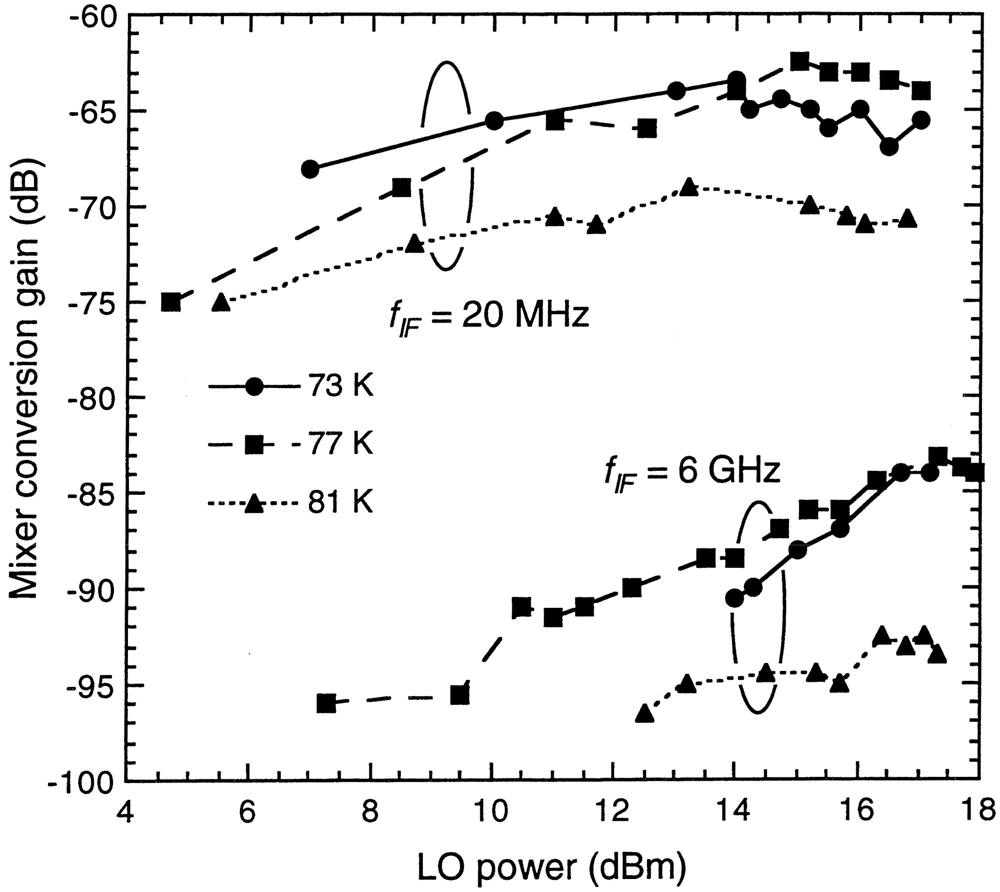

Fig. 4. Mixer conversion gain dependence on applied local oscillator (LO) power at 20 MHz and 6 GHz intermediate frequency, measured at different temperatures.