Hot Electron Superconductive Mixers

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The creation of low noise heterodyne receivers for frequencies above 500 GHz is a prime necessity in radio astronomy. The lack of success in the development of sensitive submillimeter wave mixers is a serious problem, as several projects involving radioastronomical satellites are contemplated. For frequencies between 100 GHz to 500 GHz superconducting quasiparticle mixers (SIS-mixers) offer noise temperatures T_n below the 20-fold quantum limit T_{QL} [1]. However, for submillimeter waves at frequencies above 500 GHz SIS mixers have not yet been able to be compete with ordinary Schottky mixers. Heterodyne receivers for frequencies more than one THz have so far been realized only by using the Schottky diode mixers (see e.g. [2]) and InSb mixers. In this paper we discuss the nonlinear effect related to hot-electrons in superconductors, and their potential use in low noise submillimeter wave mixer. We also discuss the results achieved so far, as well as possible future developments.

Recently we have shown that in thin ($\sim 100 Å$) and narrow ($\sim 1\ \mu$m) superconducting strips nonlinearities are present due to hot-electron effect. Both ordinary superconductors and high-T_c superconductors have been suggested [3,4].

As radiation is absorbed, the superconductivity is being suppressed, and the quasiparticle concentration increases causing a change in V-I–characteristics as shown in Fig.1. When the current flowing through the superconducting strip exceeds its critical value, the strip's state becomes resistive. The nature of this resistive state is attributed to various physical mechanisms such as (i) phase slip centers which appear at $T \approx T_c$, (ii) flow of magnetic flux vortices at $T < T_c$ and (iii) heated normal conduction domains.

In Fig.2 energy relaxation flow within the device is illustrated. A necessary condition is that there is a strong electron-electron (Coulomb) interaction to rapidly transfer the absorbed energy to all electrons (typically the time-constant τ_{el-el} is of the order of $10^{-11} - 10^{-12}$s for $T_0 \approx T_c$). It is also required that the energy transfer from the electrons to the phonons is comparatively slow i.e. τ_{el-ph} is comparatively long (the bottleneck of the process). Hence it is required that $\tau_{el-el} \ll \tau_{el-ph}$. On the other hand, since we want the time of the detection process to be short enough to allow IF-frequencies of the order of GHz, it is also necessary that $\tau_{el-ph} < 10^{-10}$s.

The time constants can be affected by a proper choice of the dimensions of the superconducting strip. The excess electron energy must first escape to the phonons in the superconducting film (time constant τ_{el-ph} which for $T_0 \approx$

T_c is of the order of 3×10^{-10} s for Nb, 10^{-11} s for NbN, and 10^{-12} s for HTS), then τ_{ph-sub} from the phonons in the film to the substrate. It is then required that the nonequilibrium phonons escape from the film into the substrate before they could be scattered by the electrons ($\tau_{ph-sub} \ll \tau_{ph-el}$). The τ_{ph-sub} time constant is affected by the dimensions of the superconducting strip i.e. $\tau_{ph-sub} \propto d$, where d is the thickness of the superconducting film. In order to avoid reverse flux of nonequilibrium phonons from the substrate to the film, the width of the film should be smaller than 1 μm.

The results for IF frequency band measurements at 150 GHz are shown in Fig.3. Summarizing the data we can expect IF band widths for superconducting mixers made of Nb to approach 500 MHz, while NbN should yield 10 GHz and YBaCuO 100 GHz.

Experimental results of conversion losses for a 100 GHz Nb mixers have been presented in [5]. The measurements show total conversion losses of 7.5 to 11 dB. Considering the mismatch loss, the convrsion loss for the mixer process itself amounts to about 1 dB only. The calculations show that positive conversion efficiency is also possible. This is due to non-equilibrium phenomena in the film causing an effective negative resistance phenomenon (see Fig.1). The ambient temperature should of course be below the critical temperature of the film. The bias conditions will be affected by the operating temperature, but can also be affected by an external magnetic field. In Fig.4 an example is shown of calculated conversion loss vs bias current (Fig.3). So far, noise has not been experimentally established. The measurements only indicate that the noise temperature is quite low. In Fig.4 we also show the calculated noise temperature for Nb mixer, assuming that the noise is only attributed to Johnson noise and thermodynamic fluctuation type noise [5].

Since the number of static defects in ultrathin films is large, the momentum relaxation time is of the order of $\tau_m - 10^{-14} \div 10^{-15}$ s, and the film should be capable of absorbing power at any frequency, e.g. from microwave to infrared frequencies, where $\omega\tau_m = 1$. Furthermore, there should be no parasitic elements such as the junction capacitance for SIS junctions or an inductance related to electron inertia, which should greatly facilitate the design of submillimeter wave mixers.

By choosing the length of the strip (of the order a of several μm), its resistance can be adjusted to 20-300 Ω, which would make it suitable for coupling to waveguides or planar antennas. For such a strip the optimum local oscillator power is of the order 10^{-6}W for Nb, 10^{-4}W for NbN and 10^{-3}W for YBaCuO. If a large dynamic range is required, several long strips can be connected in shunt.

The hot electron mixer seems to be a promising alternative in achieving low noise temperatures in the submillimeter wave frequency range, in particular for frequencies above 500 GHz. However, a lot of work still remains to be done for the final proof of their efficiency in low noise receivers.

References

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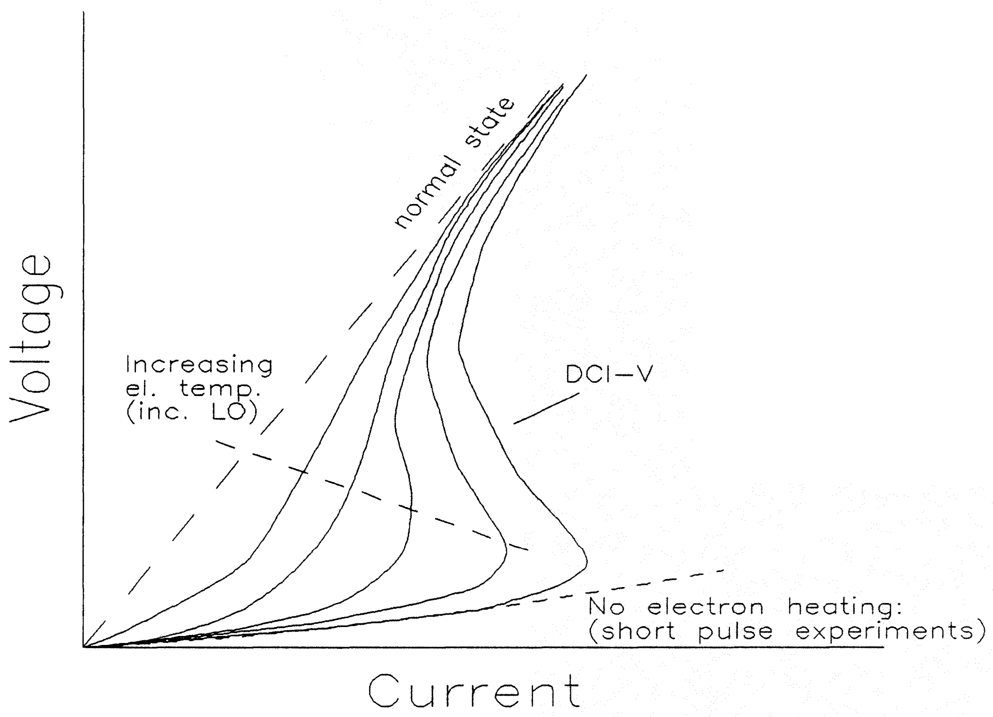

Fig.1 Schematic IV-characteristics of a thin film superconductor for different LO bias conditions.

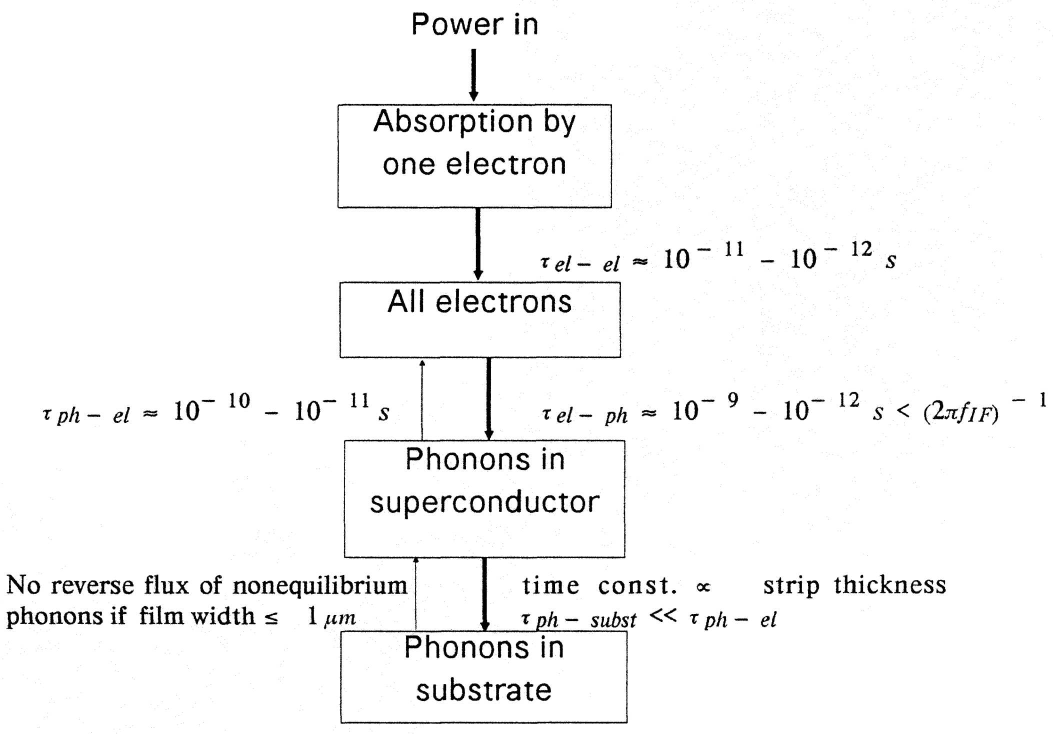

Fig 2. Shematic diagram shoing the various energy relaxation mechanisms in superconducting hot-electron devices.

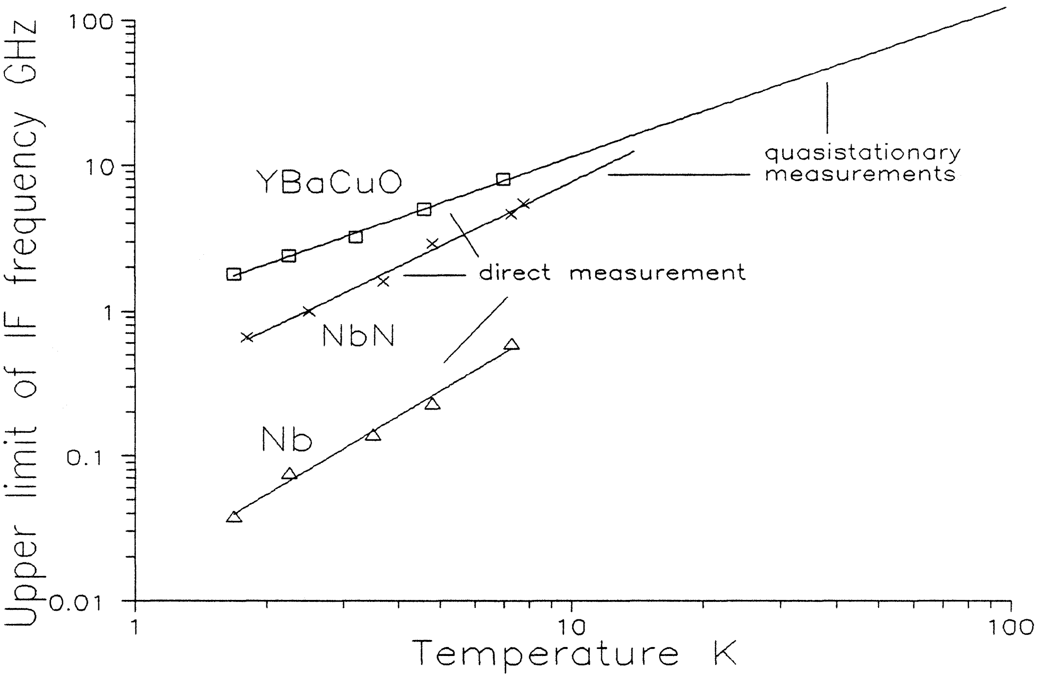

Fig.3. Upper limit of IF frequency vs temperature for Nb, NbN and YBaCuO mixers elements.

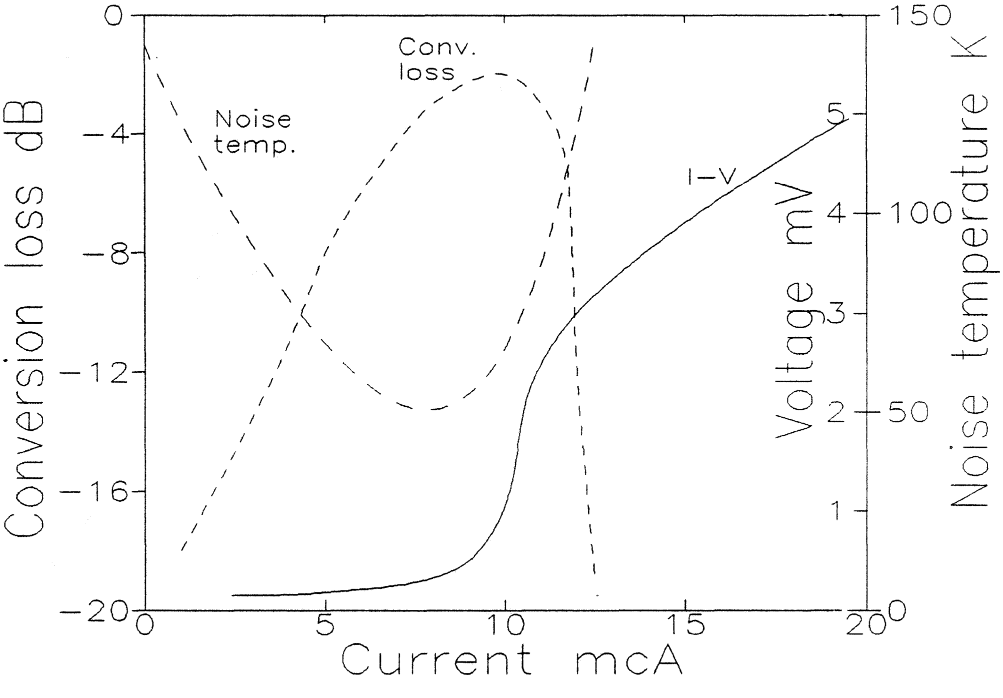

Fig.4. Culculated current dependence of conversion loss and noise temperature for a Nb mixer.