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Direct response of twin-slot antenna-coupled hot-electron bolometer mixers designed for 2.5 THz radiation detection

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We measure the direct response of a Nb diffusion-cooled hot-electron bolometer mixer in a frequency range between 0.5 and 3.5 THz. The mixer consists essentially of a twin-slot antenna, a co-planar waveguide transmission line and a Nb superconducting bridge. It is designed for use in receivers with astronomical and atmospherical applications around 2.5 THz. We calculate the impedance of the antenna, the transmission line, and the bridge separately using models which are developed for frequencies below 1 THz and predict the direct response of the mixer. We demonstrate that these models can be applied to much higher frequencies. However, the measured central frequency is 10%–15% lower than predicted. © *2000 American Institute of Physics.*
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High sensitive superconducting hot-electron bolometer mixers (HEBMs) for radiation detection at THz frequencies are required for application in atmospheric and astronomic research. In particular, detection of 2.5 THz radiation is interesting since an important spectral line of the hydroxyl radical OH appears around this frequency. Several HEBMs aiming for this frequency have been developed, showing very promising performance with regard to sensitivity.[1–3]

A sensitive mixer requires low intrinsic noise, high conversion gain, and high coupling efficiency of the radiation signal from free space to the Nb bridge. Thus, a high coupling efficiency is one of the key parameters for low receiver noise. We choose a coupling structure that consists of a twin-slot antenna and a co-planar waveguide (CPW) transmission line. Such a coupling structure has been applied for a Schottky mixer at 250 GHz.[4] A twin-slot antenna combined with a microstripline has been used for a superconductor–insulator–superconductor mixer around 1 THz.[5,6] A twin-slot antenna/CPW combination has recently been introduced for HEBMs and evaluated experimentally.[1] This work demonstrates that such a coupling structure can work even at 2.5 THz. However, the measured peak response frequency is found to be considerably lower than expected theoretically. A question arises whether models developed and partially tested at low frequencies are also applicable for predicting peak frequency and bandwidth at much higher frequencies, such as 2.5 THz.

To address this issue, in this letter we characterize the direct response of a diffusion-cooled Nb HEBM designed for 2.5 THz with a Fourier transform spectrometer (FTS) and compare the results with different models.

Figure 1 shows a scanning electron microscopy (SEM) micrograph of a mixer designed for 2.5 THz. It consists of a twin-slot antenna, a CPW transmission line, and a Nb microbridge. The CPW transmission line is used to match the impedance between the antenna and the bridge. The CPW transmission line is connected to the intermediate frequency and direct current (dc) bias contact via a quarter-wavelength ($\frac{1}{4}\lambda$) radio-frequency (rf) reflection filter. A similar structure was used by Karasik *et al.*[1]

We start by describing the model to calculate the intrinsic coupling efficiency η_{int} of the mixer, namely, the power transmitted from the antenna to the bridge. To calculate η_{int},

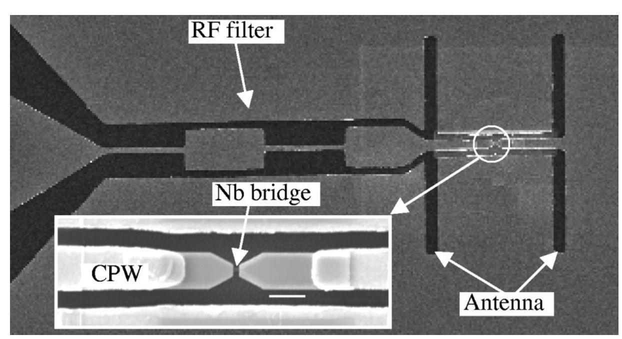

FIG. 1. SEM micrograph of a twin-slot antenna-coupled Nb HEBM. The nominal slot length L, width w, and separation s are 36.0, 1.8, and 19.2 μm, respectively. The Nb microbridge and part of the CPW transmission line are shown in the inset, where the bar represents 2 μm.

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we consider each antenna slot as a voltage generator in series with the antenna impedance. The rf choke filter is assumed in series with one voltage generator/antenna impedance. On one side, the microbridge sees an impedance Z_1 equal to the added filter and slot impedance transformed by the CPW transmission line. On the other side, only the transformed slot impedance Z_2 is present. A similar approach is used for a Schottky mixer by Gearhart and Rebeiz.[4] The intrinsic frequency-dependent coupling between the embedding impedance $Z_{\mathrm{embed}}=Z_1+Z_2$ seen at the bridge terminals and the bolometer impedance Z_{HEB} can now be calculated using

$$\eta_{\mathrm{int}}=1-\left|\frac{Z_{\mathrm{HEB}}-Z_{\mathrm{embed}}}{Z_{\mathrm{HEB}}+Z_{\mathrm{embed}}}\right|^2. \tag{1}$$

The impedance of the antenna as a function of frequency is calculated using a moment method in the Fourier transform domain, developed by Kominami, Pozar, and Schaubert.[7] In the simulation of η_{int} we take into account the decrease of the antenna-beam efficiency when the frequency is much higher than the design frequency. This effect suppresses the appearance of the second antenna resonance.[8] The characteristic impedance Z_0 of the CPW transmission line is calculated for several widths of the center conductor and the gap using a commercial software package (MOMENTUM[9]). It is important to note that the impedances of both the antenna and the CPW are calculated for printed slots at the interface between two semi-infinite regions, air and substrate. Basically, the thickness of the metal layer is fully neglected. Because of this, the effective relative dielectric constant ϵ_{eff} is $(\epsilon_r+\epsilon_{\mathrm{air}})/2$, where ϵ_r and ϵ_{air} are the relative dielectric constant of substrate and air, respectively.

The bolometer impedance Z_{HEB} can be expressed as[10]

$$Z_{\mathrm{HEB}}=Z_S\frac{l}{d}+Z_l, \tag{2}$$

where Z_S is the surface impedance of the superconducting bridge, l and d are its length and width, and Z_l the impedance due to the geometrical inductance of the bridge. Z_S reduces to the square resistance $R_\square$ when the frequency is higher than the gap frequency of the bridge and the film thickness is much smaller than the skin depth.[11] Furthermore, Z_l is small, on the order of $1i\ \Omega$ for our device. Therefore, Z_{HEB} in practice equals the normal-state resistance R_N. The effective impedance for the four-section rf filter is calculated by loading each $\frac{1}{4}\lambda$-CPW section with the effective impedance of its predecessor.

Based on this model we find the maximum coupling efficiency at 2.5 THz for the following mixer geometry: for the antenna we choose length L, separation s, and slot width w equal to 0.30 λ_0, 0.16 λ_0, and 0.05 L, respectively. Here, λ_0 is the free-space wavelength (120 μm at 2.5 THz). For the CPW transmission line we choose the center conductor width to be 2 μm and the width of both gaps 0.5 μm, giving Z_0 equal to 39 Ω. R_N of the bridge is assumed to be 75 Ω. Using these parameters, we predict a maximum value for $\eta_{\mathrm{model,int}}$ of 90%.

The device is fabricated on a Si wafer with a high resistivity (∼5 kΩ cm). The fabrication process is briefly described as follows: Nb (12 nm thick) is dc-sputter deposited and patterned as squares with an area of $12\times12\ \mu\mathrm{m}^2$ by lift-off. We restrict the presence of the Nb to the region near the bridge since Nb is rather lossy at THz frequencies. Au cooling pads are defined using electron-beam lithography (EBL) and lift-off, giving a bridge length of about 200 nm. Using deep-ultra-violet lithography, the antenna and CPW structures are defined in the Au ground plane (180 nm thick). A narrow PMMA line is written with EBL acting as an etch mask in the final Nb etch process, resulting in a Nb bridge width of 180 nm. The critical steps in this process are the definition of bridge size, the control of R_N, and the definition of the gap width in the CPW, determining its characteristic impedance Z_0. The device we focus on has a R_N of 41 Ω and CPW gap width of 0.8 μm. The superconducting critical temperature of the bridge is 4.8 K.

In order to verify the predictions, we measure the frequency-dependent response of the mixer using the HEB as a direct detector in a FTS. The FTS measurement setup consists of a Michelson interferometer with a chopped Hg arc lamp providing broadband THz radiation. One of the mirrors is fixed, while the other can be moved over a range of 32 mm with an accuracy of 5 μm. These parameters give a maximum spectral resolution and frequency range of 5 GHz and 16 THz, respectively. The beam splitter used is a 25-μm-thick Mylar sheet. To remove effects of absorption due to water, the whole optical path is in vacuum.

The device is glued onto a synthesized elliptical Si lens[12] having a radius of 5 mm and an extension length of 1.9 mm (including substrate thickness) and mounted in a standard cryostat. The window is of a Mylar sheet with a thickness of 40 μm. The heat filter is a 112 μm Zitex sheet.[13]

The direct response in current $\Delta I(f)$ is a HEBM measured in a FTS can be described by

$$\Delta I(f)=S\,\eta_{\mathrm{int}}\eta_{\mathrm{opt}}\eta_{\mathrm{FTS}}P_l, \tag{3}$$

where S is the current responsivity of the microbridge, η_{opt} the combined transmission of the window and heat filter, and η_{FTS} the power transfer function of the FTS. P_l is the power spectrum of the lamp. The current responsivity S is considered to be frequency independent as long as the frequency is higher than the superconducting gap frequency, which is justified for our devices. P_l is assumed to be a slowly varying function of frequency and can be considered constant throughout the frequency range of interest. The transmission of the lens is not included in Eq. (3) since it is assumed frequency independent.[14] Thus, the measured relative response reflects the product of η_{int}, η_{opt}, and η_{FTS}.

The direct response is measured at a constant bias voltage. The signal from the lamp is chopped with a frequency of 16 Hz and $\Delta I(f)$ is measured using a lock-in amplifier. The FTS is operated in a step-and-integrate mode with an integration time is 2 s. The spectrum is obtained by Fourier transforming the interferogram, which is apodized using a sinusoidal apodization function. The measurements are performed at a temperature close to the superconducting critical temperature T_c.

Two similar mixers designed for 2.5 THz are measured. Figure 2 shows a typical measured relative direct response. To obtain the measured η_{int}, we divide the direct response by the product of η_{opt} and η_{FTS}. This product is shown in the inset of Fig. 2. η_{opt} and η_{FTS} are based on calculations

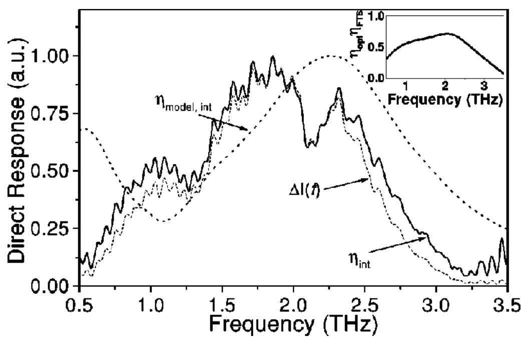

FIG. 2. Direct response of the HEBM designed for 2.5 THz as a function of frequency. The dashed line gives the measured direct response $\Delta I(f)$, reflecting the product of intrinsic coupling efficiency η_{int}, the combined transmission of the window and heat filter η_{opt}, and the power transfer function of the FTS η_{FTS}. The thick solid line represents the experimental η_{int}, while the dotted line represents the theoretical prediction $\eta_{\mathrm{model,int}}$. All curves are normalized to their maximum value. The inset shows a product of η_{opt} and η_{FTS}.

including the measured index of refraction and loss of the material used (e.g., see Ref. 15). The frequency dependence of the thin lens in the FTS is not considered. The intrinsic response η_{int} is also shown in Fig. 2. We find a peak response frequency of 1.9 ± 0.1 THz from the intrinsic mixer response, defined as the average of the two 3 dB points. The 3 dB bandwidth is about 1.3 THz. The unexpected dip around 2.1 THz is not understood but may be due to the FTS lamp.[16]

To understand this result we calculate the theoretical response $\eta_{\mathrm{int,model}}$ using the model described here. Since the actual device parameters differ from those in the initial design, the calculation of the $\eta_{\mathrm{int,model}}$ shown in Fig. 2 is done using the actual values, namely, $R_N=41\ \Omega$ and $Z_0=46\ \Omega$ for the CPW transmission line because of a larger gap (0.8 μm).

The model predicts a peak response frequency of 2.3 THz and a 3 dB bandwidth of 1.3 THz. The overall response predicted coincides well with the measured curve if a frequency down shift of about 300 GHz is introduced. By doing this, we infer a peak frequency of 2.0 THz from the measured η_{int}, consistent with the value determined from the 3 dB points.

We also calculate the relative direct response of the same mixer in an alternative way using MOMENTUM.[9] The result is, in general, consistent with the simulation shown in Fig. 2. The peak response, however, is 2.1 THz, also higher than what we measured.

In both models, the quantitative difference between the measured peak frequencies and those predicted in our calculations occurs only around 2.5 THz but not at low frequencies. We have measured and analyzed similar mixers designed for 1 THz, showing good agreement between measured and predicted response. Although our experimental study does not reveal the origin of this discrepancy, we suggest that the difference is caused by neglecting the finite thickness of the metal layer. For our devices, the thickness of the metal layer has become comparable to the gap width of the CPW. For the antenna slots at 2.5 THz, this is also the case. Reasoning qualitatively, this causes a considerable fraction of the field to run in the gap between the slot walls, giving rise to an ϵ_{eff} lower than assumed for a CPW slot in a metal film with zero thickness. This, in turn, causes the characteristic impedance of the CPW lines to rise. Calculations show that a change in characteristic impedance has more influence at 2.5 THz than at 1 THz. Furthermore, the ratio of metal-layer thickness over slot width in the antenna slots is larger in the 2.5 THz device. We suppose this changes the antenna impedance more than in the 1 THz device. Both these effects give rise to a more pronounced shift in peak frequency at 2.5 THz than at 1 THz. In order to improve the accuracy of the present models, it would be worthwhile investigating the influence of the thickness of the metal layer.

In conclusion, we have measured the direct response of Nb HEBMs with a twin-slot antenna/CPW transmission line combination around 2.5 THz and compared the results to the present models. We convincingly show that the measured direct response is 10%–15% lower in frequency than predicted by the models, although the overall shape of the spectrum agrees with the prediction.

It becomes clear now that the mixer designed using the present models will not lead to a peak response at 2.5 THz. To achieve ultimate sensitivity at 2.5 THz one can design a mixer in an engineering way by reducing the antenna size by 15% and the CPW gap size to 0.3 μm. The impedance of the HEB device is kept at a practical value of $\sim$40 Ω. Our calculations show that this does not change the peak coupling efficiency, but the size reduction may affect other properties of the antenna. A similar experimental approach has been made by Wyss *et al.*[2]

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[16] We do not attribute the dip to the device since devices with very different parameters and even different transmission lines show the dip at the same frequency.