Electromagnetic Model for Twin Slot Terahertz Mixers

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Abstract — **Twin slot antennas coupled to superconducting devices are currently being developed for terahertz mixers and direct detectors for astronomical observations. Although these mixers show promising performance in terms of noise temperature, they usually also show a considerable downward shift in the center frequency, especially when compared with calculations obtained with commonly used simplified models. This discrepancy is actually due to a variety of reasons. The impact of the bolometer-to-CPW transition, the RF choke filter and the radiation losses in the CPW line have been demonstrated in a recent study to be some of the most important reasons of the disagreement between calculations and measurements. In this paper we discuss these effects and other features, such as the silicon lens, obtaining a more robust model suitable not only for analysis but also for the synthesis of these circuits. A complete set of terahertz mixers at four different center frequencies, between 600 GHz and 2.5 THz, have been fabricated following the guidelines provided by our model and are currently being tested. The preliminary results of power coupling measured at 2.5 THz are still not as good as expected, however they show that our model is going in the right direction. With respect to previous designs, the new mixers have now a much better efficiency in terms of power coupling to the superconducting device and the center frequency shift is now decreased roughly from 30% to 10%. By the time that this paper will be published in the conference proceedings we will have more data, and we will be able to present a more extensive comparison between our calculations and measurements.**

1 INTRODUCTION

Slot antennas coupled to coplanar waveguides (CPW) are being developed for quasi-optical single-pixel detectors for use in atmospheric and astronomical instruments in the submillimeter-wave/terahertz-frequency range. Hot Electron Bolometer (HEB) mixers, for example, are often used at THz frequencies in such circuits placed at the focus of a dielectric lens. However, the measured center frequency (i.e. frequency of the peak response of the detector) is often significantly lower than that calculated with simple models. As previously indicated ([1] and reference therin), the accurate characterization of the entire mixer embedding circuit, including the parasitics associated with the geometry of the device, is needed to correctly design the circuit. Even though the geometry of these antennas, CPW lines, and devices is relatively simple, to simulate their performance in a THz circuit is not a straight-forward matter. A brute force approach based on a Method of Moments (MoM) analysis of the overall planar structure can be used, but since the device dimensions can be of the order of $\lambda_0/1000$, the numerical effort required for an accurate analysis becomes almost prohibitive, even for a single antenna.

Our model instead exploits the Method of Moments only to calculate the self and mutual admittances of the twin slot antenna. Once the input admittance is known, we introduce separately the effect of every other part of the circuit on the input impedance. First we modify the twin slot impedance by considering the presence of a silicon elliptical lens rather than a semi-infinite dielectric medium in front of the antenna. To perform this task we follow the same procedure presented in [2], with the only difference that in this paper this is only the first of several steps needed to obtain a complete description of the problem. Then we calculate the complex characteristic impedance and propagation constant of the CPW lines exploiting the formulation presented in [1] along with the geometrical reactances due to the bolometer-to-CPW transition. The effect of the RF choke filter on the input impedance is also taken into account, concluding the list of features accounted for by our model. Finally, the overall power coupling efficiency is calculated and compared with measured data.

With this model we designed and fabricated a set of HEB mixers at four different center frequencies: 600 GHz, 1.6 THz, 1.8 THz and 2.5 THz. Moreover, for each center frequency, two different bolometer-to-CPW transitions and two different bolometer lengths have been used. In total, four different mixers have been fabricated at each frequency allowing us to determine the impact of the different features on the performance.

In the following Section we first briefly describe the features of the detectors and the geometry of the circuit. Then, a detailed description of the procedure used in the calculation of the performance

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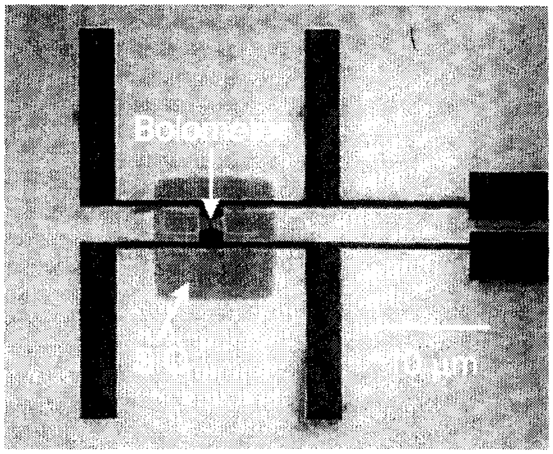

Figure 1: SEM photo of an HEB mixer embedding circuit. The superconducting microbridge is located at the center and coupled to the twin-slot antenna via CPW lines.

of the mixers is given in Section 3. In Section 4 we present the preliminary results measured at 2.5 THz and we compare them with calculated predictions. Finally in Section 5 we draw some conclusions and discuss further improvements to the model.

2 MIXER LAYOUT

A set of sixteen different HEB mixers with four different twin slot antenna designs has been fabricated and is currently being tested in our lab. The desired center frequencies are: 600 GHz, 1.6 THz, 1.8 THz and 2.5 THz. Figure 1 shows a SEM photograph of a 2.5 THz HEB mixer. The submicron-sized bolometer is connected to the twin slot-antennas via a CPW transmission line [3]. On the right, the last section of the RF band-stop filter structure is visible (a total of seven high and low impedance sections were used).

For each frequency, two different bolometer-to-CPW transitions have been designed as proposed in [1]. The first is a flared transition as shown in Fig. 2. The second is an abrupt transition obtained without any flare (see Fig. 3). In this case the transition results in being just a big step between the width of the inner conductor of the CPW and the bolometer. As explained in [1] this latter solution is predicted to reduce to the minimum the parasitic reactances due to the transition itself. Finally, two different bolometer lengths have been also used, 0.1 and 0.2 μm, while the bolometer width is always 0.1 μm. Given the different bolometers and the different transitions, the lengths of the RF choke filter

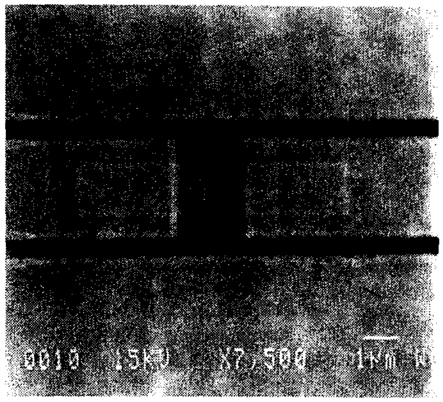

Figure 2: SEM photo of a flared bolometer-to-CPW transition. The gap length in this case is 0.2 μm.

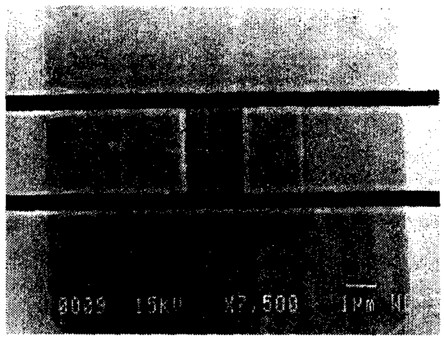

Figure 3: SEM photo of an abrupt bolometer-to-CPW transitions. The gap length here is just 0.1 μm.

sections have been also adjusted to balance the different input impedances presenting at the bolometer.

3 MODEL DESCRIPTION

The slot input impedances are obtained by means of MoM simulations restricted to the receiving slots alone, considering of course also the mutual coupling. This is the first step of the procedure to calculate the predicted response of the mixers. Then, the oscillations due to the elliptical lens are introduced. We consider the equivalent magnetic currents distribution on the two slots obtained by the MoM with the assumption that they are radiating in a semi-infinite medium. We then introduce the geometry of the dielectric lens and consider the magnetic field on the slots due to a double diffraction in the internal region of the lens. This modifies the amplitude of the equivalent magnetic currents on the slots and therefore the pertinent input impedance seen by the rest of the circuit. For more details about the formulation please refer to [2].

Once the slot impedances are calculated taking into account the presence of the lens, we introduce the effect of the CPW lines. The parameters of the transmission line are obtained using the formalism presented in [1]. The unknown magnetic currents are obtained from the direct solution of the pertinent Continuity of Magnetic Field Integral Equation (CMFIE) assuming, as in [4], the separability between transverse and longitudinal space functional dependence. In particular, the transverse electric field is assumed to be well represented by a unique edge singular function defined on each of the two slots composing the CPW. The procedure for finding the space domain magnetic current consists of: i) expanding via a Fourier Transform the transverse impressed magnetic field in spectral superposition of electric currents progressively phased by k_x; ii) finding in analytical form, for each k_x, the 2D-Green's Function (GF) by imposing the continuity of the magnetic field at the slot axis; and iii) integrating in k_x all the 2D-GF. Equating to zero the denominator of the spectral expression for the magnetic currents, a dispersion equation is obtained that, solved numerically, defines the propagation constant of the leaky mode supported by the structure.

After the characteristic impedance and propagation constant of the CPW have been calculated, we introduce the effect of the reactances due to the bolometer-to-CPW transition. Since the bolometer width is much less than the width of the CPW inner conductor, a strong inductive load is concentrated at this transition. The analysis accounts for the effect of the transition by combining two equivalent lumped reactances related to the length and width of the transition itself. An inductive reactance is derived by investigating the canonical slot problem that best fits the length of the gap. The value of this inductance depends on the actual shape of the bolometer-to-CPW transition. Finally, the expression for the inductance is evaluated analytically. A detailed description of the analytical representation can be found in reference [1].

The last step consists of the introduction of the RF choke filter. The filter (whose last section is visible in Fig. 1) consists of seven high and low impedance sections and is designed to present a "short circuit" for the RF current at the interface with the radiating slot. Actually the impedance that is facing the slot in the equivalent circuit is close to zero for the real part, but not for the imaginary part. Therefore, when we transform the filter impedance along the Smith Chart until the bolometer section of the circuit, we typically find an even bigger impedance. In particular, even if the real part does not produce a considerable effect at the bolometer section, the imaginary part instead has a big impact on the resonating properties of the circuit and therefore on the center frequency of the detector. In this procedure the filter is modeled by means of CPW transmission line setions, where the characteristic impedance and propagation constant of each section are calculated using the same formalism desribed earlier in this paragraph.

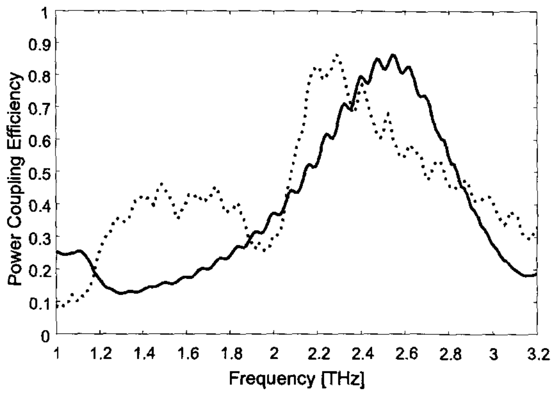

Figure 4: Comparison between measured (dotted) and calculated (solid) power coupling efficiencies.

4 PRELIMINARY RESULTS

The spectral response and hence the power coupling efficiency of a 2.5 THz HEB mixer with a flared transition has been measured with a Fourier Transform Spectrometer (FTS). The measured data are shown in Fig. 4 along with the calculated predictions. These latter are obtained assuming a bolometer resistance of 50 Ohms and the absolute amplitude reflect the expected power coupling efficiency versus frequency. The measured data are corrected for the effect of the 23 μm thick beamsplitter used in the FTS, for the 50 μm thick mylar window at the aperture of our dewar and for the frequency overmoding of the gaussian beam impinging on the silicon lens. The temperature of the mixer block was 4.2° Kelvin. Moreover, to better compare the curves, the amplitude of the measured data has been normalized to the same level of the calculated data (the FTS is relative spectral response only). Earlier measurements of a previous 2.5 THz design showed a disagreement up to 30% in the center frequency with respect to calculations performed with a previous simplified model [1]. Morevover, the bandwidth shown by the previous measurements was much broader, indicating that the power coupling efficiency of the overall circuit was poor. According to this preliminary result, our model is now able to predict the center frequency with an offset of 10% with respect to the predictions. Also, the bandwidth now is narrower and much closer to the predictions, indicating that the new design is more efficient in terms of power coupled to the device. Finally, the ripples on both the measured and calculated data are due to the effect of the elliptical silicon lens and not to the effect of the glue used to attach the antenna chip to the lens as previously thought. Other features shown by the measured data, like the sharp dip at 2 THz and the second peak at 1.5 THz, are still without a clear answer. However, considering the challenges involved in doing measurements in this frequency range, we believe that we obtained a satisfactory agreement.

5 CONCLUSIONS

We have presented an electromagnetic model which can predict with a certain accuracy the performance of twin slot antennas coupled to superconducting devices in the THz frequency range. This accounts for: the mutual coupling between the slots, the effect of the silicon lens, the power leakage of CPW lines, the effect of the bolometer-to-CPW transition and the impedance of the RF choke filter. A set of sixteen different mixers with center frequency ranging from 600 GHz to 2.5 THz has been designed and fabricated. The preliminary result at 2.5 THz shows a good agreement between measurements and calculations, although there are still some features that are not fully explained. The agreement between measurements and prediction has been improved substantially with respect to previous models, and we are presently testing the performance of other mixers.

Other aspects that probably have a considerable impact on the measurements and that are not yet taken into account by the model consist, for instance, of the ohmic losses in the overall circuit. Preliminary calculations based on simple quasi-static approximations showed that the ohmic losses could have a non-negligible impact on the measured data. However, the extremely small (in terms of wavelength) geometrical details of the structure suggest that a more deep and accurate analysis is needed before reaching any conclusion. Another issue could be related to the considerable difference in the metal film thickness. The superconducting bolometer consists of a 10 nm thick Nb film, while, for instance, the rest of the circuit is a 300 nm thick gold film. Moreover, with these thicknesses and in this frequency range, extremely anomalous skin effect should play an important role.

To conclude, we believe that our calculations can be very useful in improving the performance of THz mixer circuits.

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