Accurate Electromagnetic Modeling of Terahertz Detectors

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Abstract

Twin slot antennas coupled to superconducting devices have been developed over the years as single pixel detectors in the terahertz (THz) frequency range for space-based and astronomy applications. Used either for mixing or direct detection, they have been object of several investigations, and are currently being developed for several missions funded or co-funded by NASA. Although they have shown promising performance in terms of noise and sensitivity, so far they have usually also shown a considerable disagreement in terms of performance between calculations and measurements, especially when considering center frequency and bandwidth. In this paper we present a thorough and accurate electromagnetic model of the complete detector and we compare the results of calculations with measurements. Starting from a model of the embedding circuit, the effect of all the other elements in the detector on the coupled power have been analyzed. An extensive variety of measured and calculated data, as presented in this paper, demonstrates the effectiveness and the reliability of the electromagnetic model at frequencies between 600 GHz and 2.5 THz.

1 Introduction

Twin slot antennas coupled to coplanar waveguides (CPWs) [1] have been developed for quasi-optical single-pixel detectors for use in atmospheric and astronomical instruments in the submm-wave/THz-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. A 600 GHz design was published in 1993 [1] and since then there have been several attempts to scale the same design to much higher frequencies. However, the main problem that afflicted these scaled designs was that the measured center frequency (i.e. frequency of the peak response of the detector) was often significantly lower than that predicted with simple models. As previously shown [2], the accurate characterization of the entire mixer embedding circuit, including the parasitics associated with the geometry of the device, is the first step needed to correctly design these detectors. Measured data demonstrated that we were going in the right direction but that we were still missing some important contributions. In this paper we extend the accuracy used in modeling the embedding circuit to the whole detector. All the critical features that have an effect on the performance of the detector are now accurately modeled, from the coupling of the gaussian beam that occurs at the silicon lens, to the impedance match between bolometer and equivalent input impedance of the antenna. In the next section a brief description of the geometry of the detector is provided and the key features of the model are described. Calculated and measured data for center frequency and bandwidth are then presented in Section 3, where the predicted performance of detectors intended to work at four different center frequencies (600 GHz, 1.6, 1.8 and 2.5 THz) are compared with measurements performed in our lab. These data demonstrate that this model is now accurate enough to be used not only for the analysis (as shown in [2]) but also for the synthesis of THz mixers and circuits.

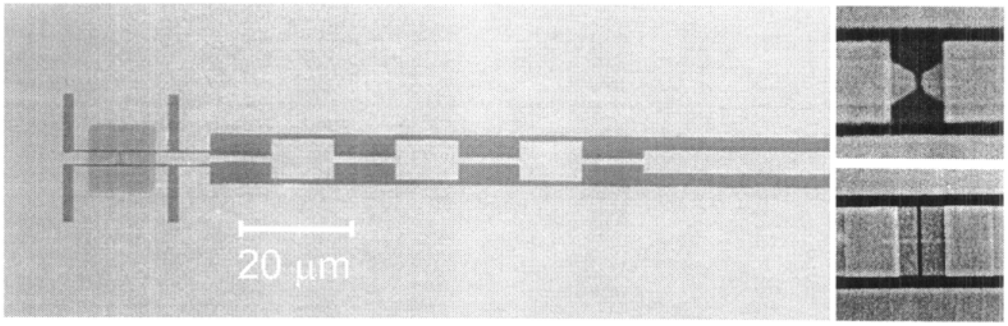

Figure 1: SEM photograph of a 2.5 THz twin slot antenna (left). The high and low impedance sections in the CPW line constitute the RF choke filter. The far right of the figure shows SEM photographs of the two different bolometer-to-CPW transitions (tapered and non-tapered) adopted for the new design.

2 Detector Geometry and Model Description

The detectors consist of a twin slot antenna with an HEB device located in the CPW line between the slots. As shown in Fig. 1, another CPW line is connected to the side of the antenna to provide an IF/DC connection. This line contains an RF choke filter to avoid the leakage of power at RF frequencies through the rest of the electronics. The antenna and the superconducting bolometer are fabricated on a silicon wafer and placed at the second focus on the backside of a silicon elliptical lens. In order to obtain better performance as compared with previous designs, several features have been modified according to the results provided by our model. Some of the improved features in the embedding circuit include the non-tapered bolometer to-CPW transition (Fig. 1), the length of the antenna slots and also the length of the RF choke filter sections. For further details about the new features included in the embedding circuit, please refer to [2] and [3]. A set of sixteen different HEB mixers with four different twin slot antenna designs has been fabricated with the following center frequencies: 600 GHz, 1.6 THz, 1.8 THz and 2.5 THz. The superconducting bolometers have been fabricated in Nb using both tapered and non-tapered transitions, with one bolometer width (0.1 μm) and two bolometer lengths (0.1 and 0.2 μm). A representation of the embedding circuit is shown in Fig. 2. In the circuit, V_s and Z_s are the amplitude and impedance of the voltage generators (the two slots), Z_f is the equivalent input impedance of the RF choke filter at the slot section, k_0 and Z_0 are the CPW propagation constant and characteristic impedance (calculated including the effects of radiation and conduction losses), Z_t is the equivalent impedance of the bolometer transition and R_b is the bolometer resistance. Also in Fig. 2, is a sketch of the silicon lens and of the antenna chip located on the back of the lens. From left to right, a gaussian beam generated by the Fourier Transform Spectrometer (FTS) impinges on the silicon lens, passes through the interface between the silicon and free space, undergoes multiple reflections inside the lens (modifying the slot input impedance) and finally couples to the twin slot antenna. Each of these steps has been modeled and its effect on the total detector loss analyzed. The gray zones in the lens drawing represent the boundaries of the field of view of the antenna, given the dimensions and thickness of its rectangular chip. This latter is 2.4 mm long (E-plane) and 1.2 mm wide (H-plane) and 0.381 mm thick; the 600 GHz design however uses a square

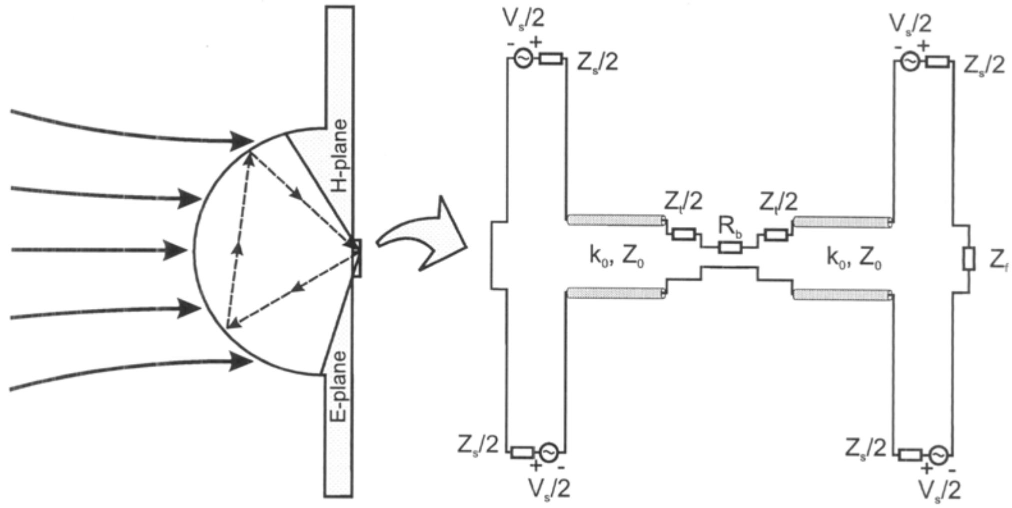

Figure 2: Geometry of the silicon lens (left) and equivalent embedding circuit of the antenna (right).

2.4 mm configuration. From the direction of maximum radiation the field of view of the antenna is limited to 72.4° in the E-plane and 57.6° in the H-plane. For the 600 GHz design, the broader field of view applies on both principal planes. The calculations performed to obtain the radiation pattern of the silicon lens and the effect of multiple reflections on the slot input impedance are based on the formulation presented in [4] and [5].

3 Measured and Calculated Data

All detectors have been measured with a high resolution Bruker HR-120 Fourier Transform Spectrometer (FTS). Fig. 3 shows a summary of all the measured (diamonds) and calculated (other symbols) center frequencies and bandwidths. On the x-axis of both graphs we have the four frequency bands under analysis while on the y-axis we have the measured center frequencies in one case and the measured bandwidths in the other. Every symbol is associated to a particular bolometer length (0.1 or 0.2 μm) and transition (tapered or non-tapered). All measured detectors show performance within a very close range of the calculations/predictions both at high and low frequency. This demonstrates that the electromagnetic model is accurate enough to tackle both the analysis and design of detectors and mixers both at frequencies as "low" as 600 GHz and as "high" as 2.5 THz without any particular problem. Such good agreement for the center frequencies is not a surprise, as shown in [2] and [3]; however, the fact that even the calculated bandwidth now agrees well with the measurements indicates that the model is actually quite complete and accurate. In particular, the calculated overall efficiency shown by the detectors now agrees very well with earlier measurements [6], confirming the accuracy of this model. To conclude, the significant improvement obtained in predicting the performance of these detectors now allows this model to be used as a reliable tool for the analysis and design of THz receivers and sensors.

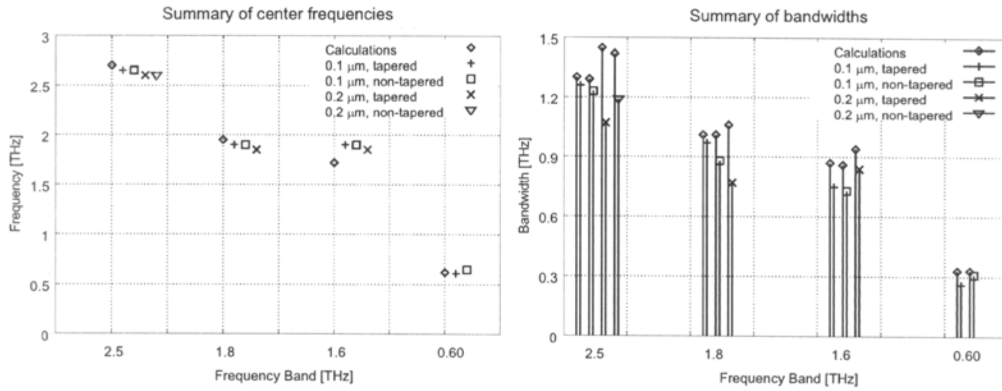

Figure 3: Summary of calculated (diamonds) and measured (other symbols) center frequencies (left) and bandwidths (right).

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