16 Pixel HEB Heterodyne Receiver for 2.5 THz

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Abstract— **A 16 pixel heterodyne receiver for 2.5 THz has been developed based on NbN superconducting hot-electron bolometer (HEB) mixers. The receiver uses a quasioptical RF coupling approach where HEB mixers are integrated into double dipole antennas on 1.5μm thick Si_3N_4/ SiO_2 membranes. Spherical mirrors (one per pixel) and backshort distance from the antenna have been used to design the output mixer beam profile. We present here the results of the antenna simulations using HFSS and ADS, as well as the beam calculations after the collimating mirror.**

***Index Terms*— HEB mixer, THz camera, NbN films, membrane.**

I. Introduction

All major ground based subMM/THz telescopes (AST/RO, CSO, JCMT, HHT, KOSMA) are now equipped with array heterodyne receivers. Two observatories which allow for observations above 1 THz will become operational in the next two years: SOFIA in 2006 and ESA's Herschel Space Observatory in 2007. SOFIA's first generation heterodyne receivers (GREAT [1] and CASIMIR [2]) are single pixel or dual pixel receivers. However two proposals for array receivers on board of SOFIA have been published. These are STAR (Universität Köln) and FAR (University of Arizona). While STAR focuses on the 1.7-1.9 THz band, FAR is going to cover a wide band from 1.5 THz to 3 THz.

NbN hot-electron bolometer (HEB) mixers [3] are currently the devices of choice for heterodyne THz receivers. Among the radioastronomical instruments where NbN HEB mixers are used are: HIFI 1.4-1.9 THz band (Herschel Space observatory); TELIS, SOFIA, Receiver Lab Telescope in Chile (SAO), APEX. A DSB noise temperature of about 450 K has been achieved for 500-700 GHz, 700 K at 1.6THz and 1100 K at 2.5 THz [4, 5, 6], 6400 K at 5.2 THz [7]. Above 1 THz there is no other device which can match this performance. The local oscillator (LO) power, required to drive an HEB mixer is 200÷300 nW (determined by the mixer size and superconducting critical temperature). Such low LO power requirements allow for use multiplier chains which produce >10 μW power up to 1.9 THz [8]. The electron energy relaxation time sets a limit for the highest intermediate frequency (IF) for the HEB mixers. For NbN HEB mixers the 3dB gain roll-off frequency is 3.5 GHz [9, 10], while the noise bandwidth is about 6 GHz. The HEB mixers can employ either waveguide (WG) or quasioptical (QO) RF coupling scheme. The development of the former has resulted in laser silicon micromachining [11], and electroplating technique [12]. Traditional machining has also been used up to 1.5 THz [13]. QO technique has been used up to 5THz [7]. Comparing both WG and QO techniques the challenge of fabrication of THz receivers consisting of tens or hundreds of pixels has to be considered. In this paper we discuss development of a QO HEB heterodyne camera for 2.5 THz with a possibility to upgrade it to higher frequencies. The philosophy of our design is to have as more integrated components as possible. Such integration could be organized on a pixel bases (completely integrated pixels, separate pixels compose the array) or on an array bases (separate parts common for the whole array). We have chosen the second option, i.e. the camera consists of a detector array, optic array, etc.

Lens antennas have been the most popular solution in QO receivers. A large variety of antenna types has been studied: double slot, double dipole, spiral, log-periodical, ring slot, etc. The choice of the antenna is determined mainly by the input bandwidth and the embedding impedance. The beam properties are almost the same for all these antennas and are defined by the lenses. The antennas are fabricated on a dielectric (semiconductor) wafer and are placed on the back side of a spherical or elliptical lens. The lens eliminates substrate mode loss, which is otherwise unavoidable since the wafer thickness is larger than the THz wavelength. Beams with up to 90% Gaussicity can be achieved with the lens/antenna approach. This has been experimentally verified at subMM wavelengths. The antennas (integrated with mixers) are fabricated lithographically and can be numbered hundreds and thousands on a single wafer.

Two concepts for the QO arrays exist. The first one is the so called fly-eye approach [14]. In this case a lens is integrated with a single detector (mixer). Then, the lenses (one per pixel) are integrated in a 1D or 2D arrays. The array's filling factor is limited by the lens diameter, i.e. the detectors can not be positioned closer to each other than the lens diameter. The lens diameter can be reduced at the expense of the angular dimension of the beam (the diffraction limited beam has a divergence angle of $F/(D\lambda)$, where F is the focal distance, D is the lens diameter, and λ is the wavelength). The fly-eye approach requires also a large amount of lenses and assembly

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procedures. However, it is quite a straightforward approach and it is suitable for small size THz arrays.

In the second array concept a single lens is used for the whole array [15]. In this case the detector array is made on a separate wafer and it is attached to a single lens. The lens has to be big in order to minimize the risk of the beam distortion. The beam distortion comes from the fact that all detectors but one will be placed off-axis of the lens. The distortion increases with the ratio of *D/d,* where *d* is the distance from the antenna to the lens's main optical axis. However, much larger array filling factors can be achieved. In this case the minimal interpixel distance is limited by the antenna dimensions (typically of the order of the wavelength) and by the on-chip read- out electronics.

A QO RF coupling scheme can be also realized without lenses when the antenna is placed on a substrate which is much thinner than the wavelength. It has been shown, that in order to avoid substrate modes the substrate has to be not thicker than $0.02\lambda_e$, where λ_e is the wavelength in the dielectric, i.e. of the order of 1 μm thick. Such thin substrates are possible to obtain by utilizing SiO_2/Si_3N_4 membranes [16]. For 2.5 THz λ_e=47 μm (in SiO_2/Si_3N_4), therefore $0.02\lambda_e$ =1 μm. An interesting approach has been proposed in [17] where a Double Dipole Antenna (DDA) on a membrane backed with a back short was in the focus of a small parabolic reflector. 37 dB reflector gain was achieved at 2.5 THz with about 10% bandwidth. We adopted this approach for the HEB mixer camera which we present below.

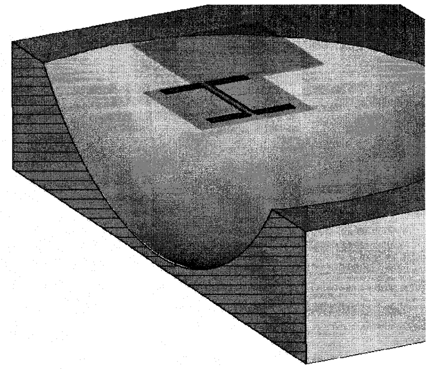

Fig. 1. A single pixel layout. The HEB mixer is integrated in a planar antenna with a backshort to minimize the back lobe loss. Both antenna and the backshort are placed on thin membranes above the collimating mirror.

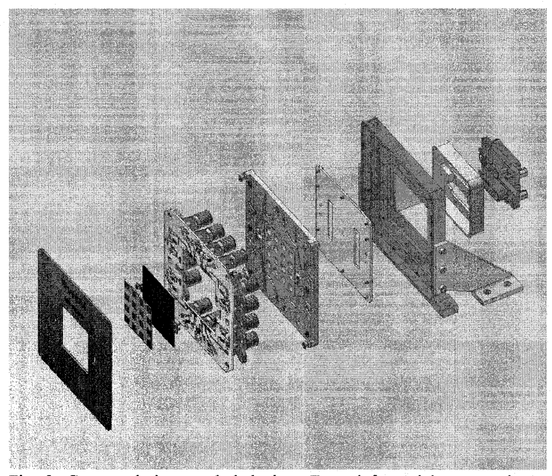

Fig. 2. Camera design: exploded view. From left to right: protection cap, backshort wafer, HEB wafer, IF board, mirror plate, dc board, housing, dc connector holder, dc connectors.

II. Camera design

A. Camera architecture

A single pixel optical scheme is shown in Fig. 1. The DDA antenna is placed on a stress less Si_3N_4/SiO_2 membrane which is 1.5 μm thick. A backshort (above the DDA) reduces the back lobe and increases the beam directivity. A spherical (or parabolic) mirror collimates the beam. Our design is 4x4 pixel. All 16 DDA/HEBs are fabricated on a single silicon wafer (see in this proceedings [18]). The backshort array is fabricated by a similar technique on the same type of membrane, and it is fixed on top of the HEB array. The mirror array is made on a single plate which minimizes the assembly of the camera. The HEB array is bonding to a single IF board which includes bias-Ts, and IF connectors for all 16 channels (see Fig. 2). The distance between pixels was chosen from the Airy disk diameter ($A=2.44\lambda F/D$, F being the F-number of the telescope and D is the telescope diameter). We used SOFIA telescope specifications as a mark. At 2.5 THz, we have $A_{2.5}$ = 5738 um. We fixed the distance between pixels at 6mm. Since the radiation has to go through the HEB wafer once again after reflection from the collimating mirror, we minimized the IF read out line width and lead them in a way not to obscure the beam propagation.

B. Antenna simulations

We used commercial software such as HFSS, ADS and CST Microwave Studio in order to simulate the response of an DDA with a backshort. Dipole antenna theory was used for an initial approximation [19]. The real and imaginary part of the antenna impedance (as seen in the HEB terminals) was obtained as function of frequency (Fig. 4) and the antenna geometry and the impedance matching network (Fig. 3) was optimized that the real impedance at the resonance frequency (2.5THz in our case) was acceptable for an HEB mixer (about 100 Ohm). The antenna response was estimated from antenna S11 parameters (Fig. 5). The results of the simulation were verified by comparing the published double slot antenna designs (DSA) on silicon against experimental results (e.g. [20]).

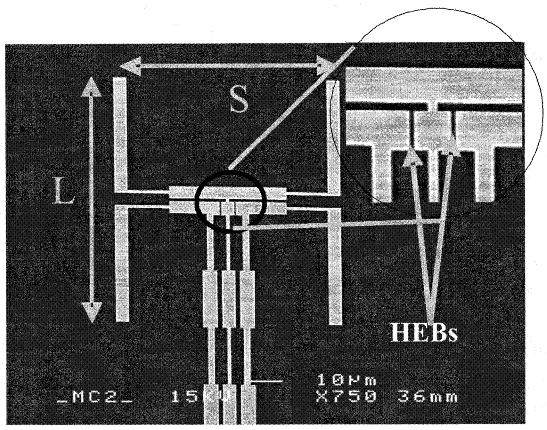

Fig. 3. A scanning Electron Microscope image of the Double Dipole Antenna with the choke filter. Two section impedance transformer is used to match the HEBs to the dipole antenna. L=82μm, S=66μm, w=4μm.

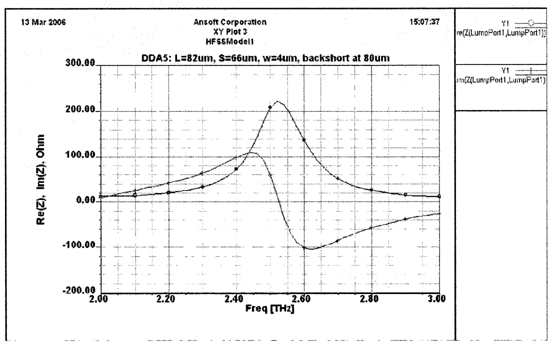

Fig. 4. Simulation of the impedance (real and imaginary part) of the DDA at the HEB terminals.

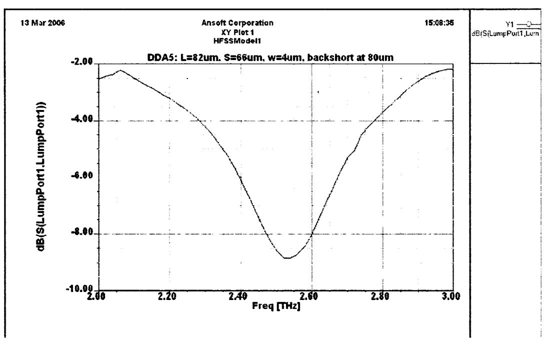

Fig. 5. Simulation of the S11 parameter of the DDA loaded on two parallel HEBs with 200 Ohm each.

C. *Beam simulations*

The far filed of the DDA was simulated with the same software. We have found that ADS simulations are fast and differ from HFSS and CST only at the angles more than ±60° (the far field always tends to zero at 90° in ADS). 3D simulators (HFSS and CST) require much more time and computer resources. However they provide more precise results (Fig. 6). We verified the validity of our calculations by comparing DSA and DDA beam simulations to those published by other authors (both theoretical and experimental). We have found that withdrawing the backshort from the DDA (on the membrane) the beam directivity increases, however the side lobe level increases. In order to keep the collimating mirror small enough (about 3mm in diameter) with the DDA at the mirror's focal plane, the beam FWHM has to be within 40°. In this case the edge taper on the 3mm mirror will be below -20dB. With the backshot at 80μm from the antenna we obtain the DDA beam FWHM to be about 32° (Fig. 6) with the side lobes below -10dB. The main beam can be approximated by a Gaussian beam with the waist of w_{01}=75 μm. For a spherical mirror (R=5.56 mm) the output beam pattern was calculated for several DDA positions using GRASP (Fig. 8). For the mirror- to- DDA distance of 2.2 mm the output beam waist is w_{02}=0.6 mm. We shall note that by using parabolic mirrors with f-numbers smaller than for spherical mirrors the DDA can be positioned closer to the mirror. Therefore the backshort can be put closer to the DDA. It will result in lower side lobes with still low beam truncation at the mirror edges.

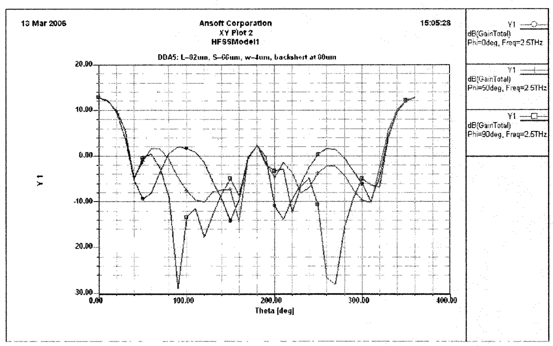

Fig. 6. Simulation of the DDA (on membrane) far field beam pattern (with a 200 μm x200 μm backshort at 80 μm above the antenna plane).

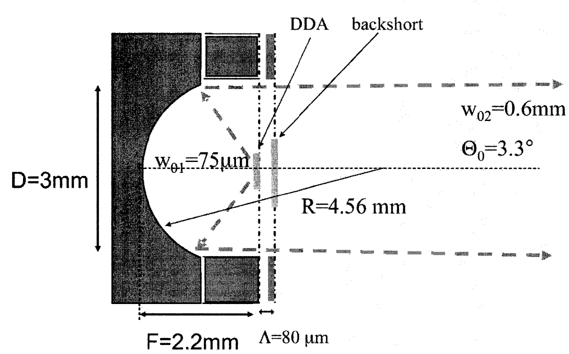

Fig. 7.The beam tracing from the DDA through the collimating mirror. The DDA beam was approximated (using Fig. 6) as a Gaussian beam with a waist of 75 μm. The output beam has a waist of 0.6mm which corresponds to the divergence angle (by $1/e^2$) of 3.3°. The calculations are done for 2.5 THz.

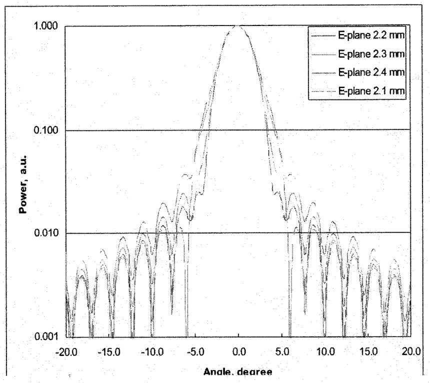

Fig. 8. Beam patter of the DDA/spherical mirror system. The mirror is 3mm is diameter sphere with the radius of curvature of 4.56 mm. The beam waist is 0.6mm when the DDA is 2.2mm away from the mirror apex.

III. Conclusion.

In the conclusions we can summarize that: the HEB technology allows design and fabrication of heterodyne cameras from both LO power requirements (not more than 200 nW per pixel), and noise performance ($T_r \approx 10hv/k$), quasioptical mixers on membranes enable quite straightforward fabrication of arrays of 16 pixels and more; the approach can be scaled up in frequency without any substantial redesign; such software as ADS, HFSS, CST Microwave Studio can be used for simulations of both S-parameters and beam properties of THz planar antennas.

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