Low noise THz NbN HEB mixers
for radio astronomy:
Development at Chalmers/ MC2

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Introduction to HEBs

\[ R(T) \text{ dependencence for 3.5nm thick NbN film} \]

\[ \text{Substrate radiation} \]

\[ \tau_{ph-e} = \tau_{e-ph} \times \frac{C_p}{C_e} > \tau_{esc} \]

\[ \text{Power in, } h\nu \]

\[ \text{One electron} \]

\[ \tau_{e-e} \]

\[ \text{All electrons} \]

\[ C_e, \Theta \]

\[ \tau_{e-ph} \sim \Theta^{-n} \sim 10\text{ps} \]

\[ \text{Phonons} \]

\[ C_{ph}, T_{ph} \]

\[ \tau_{esc} = 4d/\alpha u \]

\[ d=3-4\text{ nm} \]
Summary of the THz heterodyne receiver performance
(1-2GHz IF band)

![Graph showing performance of various THz heterodyne receivers](image)

- HEB-CTH
- HEB-DLR-MSPU
- SIS
- Schottky mixers at 300K
- HEB-SAO
- Flo, THz
- 2hf/k
- Schottky mixers at 20K

The graph plots DSB Tr, K against LO frequency, THz.
**Spiral antenna integrated NbN HEB mixer around 1 THz.**

\[ 10^{9} \times 1.81 \times 10^{-8} = 0.976 \]

After removing the input optical loss:

at 1 THz the HEB mixer noise temperature is 400K.

IF = 1.5 GHz

Bath Temperature = 2 K

30% reflection loss on Si Lens:
no AR coating

10% beamsplitter loss + 30 K

Air transmission: 0.5m, 40% RH;
1 GHz RBW
Herschel Space Observatory: Band 6 Mixer
Main Requirements

<table>
<thead>
<tr>
<th>Band 6 Low</th>
<th>Band 6 High</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Tr, at 2 GHz</strong></td>
<td><strong>Tr, at 2 GHz</strong></td>
</tr>
<tr>
<td>LO Frequency</td>
<td>LO Frequency</td>
</tr>
<tr>
<td>GHz</td>
<td>GHz</td>
</tr>
<tr>
<td>Required</td>
<td>1420</td>
</tr>
<tr>
<td>K</td>
<td>1300</td>
</tr>
<tr>
<td>Goal</td>
<td>800</td>
</tr>
</tbody>
</table>

*The IF bandwidth: 2.4 – 4.8 GHz*

*The receiver noise bandwidth (2 times increase of Tr from its value at zero IF)*

**Baseline:** 5 GHz  
**Goal:** 7 GHz

**PLO**
not more than 400 nW
3.5 nm NbN superconducting films on Silicon

Quasioptical RF coupling

Normal metal (Au) Double Slot Antenna

<table>
<thead>
<tr>
<th>frequency (THz)</th>
<th>L (μm)</th>
<th>S (μm)</th>
<th>W (μm)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1.6</td>
<td>56</td>
<td>32</td>
<td>4</td>
</tr>
<tr>
<td>1.8</td>
<td>50</td>
<td>28</td>
<td>3.6</td>
</tr>
</tbody>
</table>

Signal (A.U.) vs Frequency (THz)

2006-06-19 RadioNet Workshop, Sergey Cherednichenko Gothenburg, Sweden
NbN HEB mixers for Herschel Space Observatory: Chalmers (Sweden) + JPL(USA)

Band 6 Low (1.4-1.7 THz) \( P_{\text{LO}} < 200 \text{nW} \)

Band 6 High (1.6-1.9 THz)
Truncated elliptical lens
(a common lens design for both 6L and 6H sub-bands)

Ellipticity = 1.0193
Lens Length = 3.304 mm

The F#= 4.25 beam is insured by:

- HEB on Lens alignment: \( \pm 1 \mu m \)
- Lens extension: \( \pm 3 \mu m \)

W. Jellema et al., ISSTT2005

1.5 THz
Lens is firmly held by a torroidal spring

- Lens clamp
- Lens spring

<table>
<thead>
<tr>
<th>Deflection</th>
<th>Force</th>
</tr>
</thead>
<tbody>
<tr>
<td>5%</td>
<td></td>
</tr>
<tr>
<td>35%</td>
<td></td>
</tr>
</tbody>
</table>
DC Assembly: ESD protection, current read-out

HEB-chip wire bonded to the IF Board
Acceptance vibration test at SAAB-Ericsson Space: X-, Y, and Z- axes.

Qualification model vibration: up to 50G

Other qualifications:
1. Life time (accelerating aging tests)
2. EMC shielding
Two Flight Models prior delivery to SRON
Quasioptical 1.9 THz HEB mixer for TELIS:

simplified mixer unit

IF band: 4-6 GHz; average Tr= 2300 K.

The mixer has been delivered to DLR/ Oberpfaffenhoffen (Dr. M.Birk)
Multipixel HEB heterodyne receiver
HFSS and ADS for planar antenna simulations of ADS on silicon ($\lambda_e = \frac{\lambda_0}{\varepsilon^{0.5}}$)

**Comparison with measurements results published in R. Wyss (ISSTT 2000)**

<table>
<thead>
<tr>
<th></th>
<th>L, $\mu$m</th>
<th>simulations</th>
<th>measurements</th>
<th>ADS simulation (this work)</th>
</tr>
</thead>
<tbody>
<tr>
<td>mixer 1</td>
<td>26</td>
<td>2.98 THz</td>
<td>2.22 THz</td>
<td>2.25 THz</td>
</tr>
<tr>
<td>mixer 3</td>
<td>36</td>
<td>2.31 Thz</td>
<td>2.02 THz</td>
<td>1.95 THz</td>
</tr>
<tr>
<td>mixer 5</td>
<td>44</td>
<td>2.01 THz</td>
<td>1.60 THz</td>
<td>1.7 THz</td>
</tr>
<tr>
<td>Im(Z)=0</td>
<td>S11 to $\approx$100Ohm</td>
<td>Im(Z)=0</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

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On an electrically thin substrate \( d \ll \lambda_e \): \( \lambda_e \approx \lambda_0 \), i.e. antenna becomes a factor of \( \varepsilon^{0.5} \) larger.

Membrane antenna above an integrated mirror

\( (J. \text{ Baubert, 2004}; \text{ and } D. \text{Filipovic, 1992} \)

Model includes double dipoles, coplanar HEB feed, and RF choke.
Double Dipole Antenna Design: \( L=82 \, \mu m, \quad S=66 \, \mu m, \quad w=4 \, \mu m, \quad \Lambda=80 \, \mu m \)

Impedance at the HEB port

Reflection from the HEB port: 100 Ohm HEB

HFSS

ADS
Back-short position relative to the antenna is a very crucial parameter, which defines the beam width.
Double Dipole Antenna Design: \( L = 82 \, \mu m, S = 66 \, \mu m, w = 4 \, \mu m, \)

Backshort is \( \Lambda = 80 \mu m \) from the DDA: the most narrow beam with the side lobes < -10 dB

As \( \Lambda \) increases: the side lobes increase but the beam width decreases.
The beam pattern after the mirror.

The DDA beam is approximated as Gaussian with $w_0=75 \, \mu m$.

The DDA-mirror distance error of 0.1mm can be allowed.
$A = 2.44 \lambda F/D \approx 6 \text{mm}$ for SOFIA Telescope at 2.5THz. 
$D < A$, i.e. the mirror diameter is limited by the inter-pixel distance.

Prototype drawing of the HEB array and the Backshort array.
* all drawing dimensions in mm

Bulk substrate (Si/SiO/SiNx).
Complete thickness is 0.39 mm.

SiNx membrane, 0.0015 mm thick

Double Dipole Antenna

TF read-out

Bonding pads (Gold - 0.0005 mm thick)
4 x 4 pixel camera:
2D HEB array is fabricated on a single silicon wafer
2D mirror array is fabricated from a single aluminum plate
Fabrication of HEB mixers on $\text{Si}_3\text{N}_4/\text{SiO}_2$ membrane

1. Deposition of an NbN film by dc reactive magnetron sputtering.

2. Patterning of antenna & etc.

3. Etching NbN through the protection mask.

4. Etching of $\text{Si}_3\text{N}_4/\text{SiO}_2$ double layer

5. Etching of bulk-Si

Each membrane is 5x5mm$^2$
NbN HEB mixers gain bandwidth

All devices the width was $a=3.5 \, \mu m$, length $b=0.4 \, \mu m$, film thickness $d=3.5 \, nm$.

<table>
<thead>
<tr>
<th>Device ID</th>
<th>S001-16</th>
<th>S001-4</th>
<th>S08-n</th>
</tr>
</thead>
<tbody>
<tr>
<td>Normal resistance, $R$ (Ohm)</td>
<td>210</td>
<td>212</td>
<td>111</td>
</tr>
<tr>
<td>Critical current at 4.2K/in the cryostat, $I_c$ ($\mu A$)</td>
<td>105/ 65</td>
<td>100/ 62</td>
<td>320/320</td>
</tr>
<tr>
<td>Critical temperature, $T_c$ (K)</td>
<td>7.2</td>
<td>7.2</td>
<td>9.5</td>
</tr>
</tbody>
</table>

s08_n (bulk-Si)

NbN HEB mixer on bulk silicon was used to calibrate the set-up.
Gain bandwidth of NbN HEBs on

1.5 μm Si3N4 /SiO2 membrane

Si3N4 /SiO2 on bulk silicon
Resolution of the gain bandwidth for the HEB mixers on membranes

- A buffer layer between NbN film and Si$_3$N$_4$ : e.g. MgO.
  - a) improves the surface quality (non-defuse phonon scattering)
  - b) increases Tc of NbN films: 8K for Si$_3$N$_4$, and 11K for MgO / Si$_3$N$_4$.

- Membrane made of silicon: e.g. Silicon-on-Insulator (SOI). 3μm membranes can be made.
Perspectives for heterodyne cameras for THz frequencies

1. Planar antennas on silicon will be quite small, but still doable for at least 2 - 5 THz.

2. If so, it will be also possible just to multiply Hershel-like HEB mixers by a factor of 10-100 (depends on the available funds).

3. “Integrated” mirrors can be made as integrated arrays.

4. Mirror approach can be scaled to higher frequencies.

5. It is not known if one can make array lenses, i.e. on a single silicon wafer.

6. It has been demonstrated (G.Gol’tsman et al) that at 30THz directly absorbing HEB mixers (w/o antennas) work successfully. Shall it hold at 2-10THz? We will know soon.

7. For the last case one will probably need a single LO (QCL ?) per pixel.