# The sensitivity and IF bandwidth of waveguide NbN Hot Electron Bolometer mixers on MgO buffer layers over crystalline quartz

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We have developed and characterized waveguide phonon-cooled NbN Hot Electron Bolometer (HEB) mixers fabricated from a 3-4 nm thick NbN film deposited on a 200nm thick MgO buffer layer over crystalline quartz. Double side band receiver noise temperatures of 900-1050 K at 1.035 THz, and 1300-1400 K at 1.26 THz have been measured at an intermediate frequency of 1.5 GHz. The intermediate frequency bandwidth, measured at 0.8 THz LO frequency, is 3.2 GHz at the optimal bias point for low noise receiver operation.

### Introduction

Receivers with large intermediate frequency gain bandwidth are very important for practical radio astronomy applications. This is especially true for the observation of distant galaxies, where spectral linewidths are large. Furthermore, when a low power solid state source is used in conjunction with a Martin-Puplett interferometer (MPI) to couple signal and local oscillator (LO) to the mixer, it is desirable to operate at relatively high intermediate frequency (IF) to maximize the usable IF bandwidth.

In the past decade the hot-electron bolometric (HEB) mixer has emerged as the mixer of choice for low noise heterodyne receivers operating above 1 THz.<sup>1,2</sup> The strong need for sensitive, broadband receivers operating at THz frequencies for ground based, air-

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and space borne observatories, has helped to stimulate the development of HEB mixers, and rapid progress in their development has been made.<sup>1,2,3</sup>

Quasioptical NbN HEB mixers integrated with a planar antenna typically employ Si, MgO, or sapphire, as the substrate material. Using a thin 3 nm thick NbN film these mixers exhibit high critical temperature 9-11 K, and relatively good acoustic transparency to the substrate.<sup>3,4</sup> As a result, wide IF bandwidths, up to 5 GHz have been reported.<sup>5</sup> However, it is considerably more difficult to optimally couple the emergent beam of the planar antennas to a telescope than to couple that from a scalar feed, typical of waveguide-based mixer.

Due primarily to its low dielectric constant, and ease of processing and handling, traditional waveguide-based THz mixers employ quartz as the substrate of choice. However, for phonon-cooled NbN HEB mixers made from 3-4 nm NbN film deposited directly on crystalline quartz, the IF bandwidth is limited to about 2 GHz.<sup>2</sup>

It has been established that in NbN HEB mixers the electron energy relaxes through interaction with phonons that escape from the film to the substrate. Consequently, the IF bandwidth is a function of film parameters, the thickness *d*, critical temperature  $T_c$ , and acoustic match,  $\alpha$ , between film and substrate. In the past few years a systematic study of phonon-cooled HEB elements based on film deposited on silicon and sapphire substrates, has shown that phonon escape time ( $\tau_{esc}$ ) is equal to 12*d* ps/nm,<sup>4</sup> and for MgO substrates a phonon escape time of 6*d* ps/nm has been established.<sup>6</sup>

In order to increase the IF bandwidth of waveguide-based HEB mixers, we have investigated the use a buffer layer which may improve the acoustic match between the NbN film and the crystalline quartz substrate. Since MgO has the same crystalline structure as the NbN film,<sup>7</sup> a number groups have reported on the use of MgO as a buffer layer for Si, sapphire,<sup>8,9</sup> and quartz<sup>10</sup> substrates. The introduction of a MgO buffer layer could potentially improve the acoustic match between the film and substrate material and then reduce  $\tau_{esc} \propto d/\alpha$ . In this paper, we report on the experimental results of sensitivity and IF bandwidth of NbN based HEB waveguide mixers with MgO buffer layers.

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#### The mixers elements and experimental setup

In our experiments we used mixer elements made from high purity 3-4 nm thick NbN film. The NbN films are deposited using reactive magnetron sputtering in an argonnitrogen gas mixture on a 200 nm thick MgO buffer layer deposited on top of a z-cut crystalline quartz substrate. The critical temperature ( $T_c$ ) of these films is about 8 K and the transition width is about 0.8 K. The films are patterned by optical and e-beam lithography to give 1-2 µm wide single bolometric elements. The 80-150 nm long mixer elements are formed across two overlaid Au-Ti electrodes, which also act as coupling antennas to the waveguide. After deposition, the wafer is first diced into small blocks about 5 mm square, which are then lapped and polished to a thickness of 30 µm for 0.6-0.8 THz operation, and 23 µm for 1-1.26 THz operation. The blocks are then diced into individual HEB mixer chips: 120 µm wide × 2000 µm long and 90 µm wide×1500 µm long for 0.6-0.8 THz and 1-1.26 THz operation respectively. We have tested devices with normal-state resistance,  $R_N$ , between 80 and 170  $\Omega$ , and critical currents between 110 and 160 µA.

For tests, the individual mixer chips are mounted into a suspended microstrip channel across a reduced-height waveguide mixer block. The block is installed in a liquid helium dewar and signal input to the mixer provides via a corrugated waveguide feed horn and a 90° off-axis parabolic mirror.

For our measurements we are able to provide sufficient LO power using a solidstate LO units, which generally consist of a Gunn oscillator followed by two stages of frequency multiplication. These units allow us to make measurements continuously from 1.017 to 1.035 THz and at 1.267 THz, and deliver 5-7  $\mu$ W and 2  $\mu$ W respectively. The beam from the LO assembly is collimated using a 90° off-axis parabolic mirror, a MPI positioned in front of the cryostat window is used to combine signal and LO at the cryostat input.

DC bias is applied to the mixer via the third port of a circulator inserted between the mixer and a low noise cryogenic HEMT amplifier. After a second stage of room temperature amplification, the IF signal passes through a 100 MHz wide bandpass filter,



Fig.1 The I-V curves of the HEB mixer at the operating point with and without LO drive at 1.035 THz Also shown is the IF output power in response to hot (295K) and cold (77K) loads placed at the receiver input. The optimal bias point is shown by the open circle, and the measured Y factor is 1.2.

centered at 1.5 GHz, to a calibrated power meter which is used to measure the IF power output.

#### **Experimental results and discussion**

The current-voltage characteristics of one of the devices with and without LO power at 1.035 THz are shown in Fig.1, the receiver output in response to hot and cold loads is also shown. Optimal sensitivity is achieved at a bias voltage of 0.7 mV and a bias current of 23  $\mu$ A. At this operating point the measured receiver noise temperature is about 1000 K, and the conversion efficiency is estimated to be -14 dB. From the figure we see that the noise performance and the mixer conversion efficiency go down strongly towards higher bias voltage. In our measurements the mixer was not influenced by direct detection: the bias current change in passing from a cold to an ambient input was less than 0.2%. The



Fig.2. Spectral response of the HEB mixer measured by FTS in direct detection mode (solid curve) and heterodyne mode using Y-factor method (triangle points) as a function of frequency.

receiver also demonstrates reasonable amplitude stability, and output power fluctuations are less than 2% over a 15 min time interval.

In addition to heterodyne measurements, we have also used the Fourier Transform Spectrometer (FTS) to measure the spectral response of the same mixer. In this case the mixer was operated as a direct detector at an elevated bath temperature. The operating bias point was set at the same as for heterodyne operation, even though the general shape of the response was found to depend only weakly on the bias point. The FTS response is shown in Fig.2, solid line. From the graph we estimate that the input bandwidth is about 400 GHz. The dip around 1.15 THz might be explained by a strong atmosphere water absorption line. Other mixers have been measured using the FTS, they all demonstrate a similar bandwidth, however the center frequency shifts, by ~10%, depending on the length of backshort and the detailed layout of IF filter. The measured Y-factor from heterodyne measurements, as function of LO frequency, is also shown in Fig.2. There is reasonable correlation between the direct and heterodyne responses. For example, in general the measured receiver noise



Fig.3. IF bandwidth measurements at  $f_{\rm LO} = 0.8$  THz for different bias voltage operating points at constant LO power level. Optimal noise performance is obtained at 0.7 mV bias. Data points are fitted to the curve  $1/[1+(f_{\rm IF}/f_{\rm 3dB})^2]$ . Arrows indicate  $f_{\rm 3dB}$  for the different curves.

temperature is approximately 1K/GHz, which is comparable to that of HEB mixers, which are based on NbN film directly deposited on crystalline quartz.<sup>2</sup> The measured Y-factor at 1.26 THz LO frequency was 1.16, which corresponds to noise temperature of about 1300 K.

IF bandwidth measurements have been performed at an LO frequency ( $f_{LO}$ ) of around 0.8 THz. The receiver output as function of IF for one of the mixers is displayed in Fig.3. The experimental data are fitted to  $1/[1+(f_{IF}/f_{3dB})^2]$ , where  $f_{3dB}$  is the 3dB cut-off frequency. At the optimal bias setting for low noise performance, 0.7 mV,  $f_{3dB}$  is about 3.2 GHz (curve 1). This is significantly higher than the IF bandwidth of HEB mixers with no buffer layer.<sup>2</sup> Curves 2 and 3 are from measurements at bias voltages of 1.4 and 2.8 mV respectively, with the same LO power as at 0.7 mV bias. At high bias, 2.8 mV, the fitted  $f_{3dB}$  strongly increased up to 8.8 GHz, confirming results reported by others groups.<sup>3,11</sup> Although high IF bandwidth can be obtained at high bias voltage, figs. 1 and 3 clearly demonstrate that this is obtained at the expense of noise performance and conversion efficiency. Furthermore, there is a fundamental instantaneous bandwidth limit, which is set by the electron-phonon interaction time  $\tau_{e-ph}$ , which has been measured for thin NbN films as <sup>12</sup>

$$\tau_{e-ph} = 500 \cdot T^{-1.6} \, [ps],$$

where T is physical temperature in Kelvin. At  $T_c=8$  K, this equation yields  $\tau_{e-ph} \sim 18$  ps which corresponds to 3dB cut-off frequency of about 9 GHz. If thin NbN films can be made with  $T_c$  approaching the bulk value then it may be possible to have low noise heterodyne operation with instantaneous bandwidth in excess of 20 GHz using NbN thin film technology.

In conclusion, the employment of a MgO buffer layer has allowed us to increase the IF bandwidth of NbN waveguide HEB mixers without degrading their noise performance. Specifically, we have extended the IF bandwidth of our NbN HEB mixers to 3.2 GHz.

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