Vector Measurement of the Beam Pattern of a 1.5 THz Superconducting HEB Receiver

C.-Y. Edward Tong, Denis N. Loudkov, Scott N. Paine, Dan P. Marrone, and Raymond Blundell

***Abstract*— Near-field vector beam pattern of the 1.5 THz superconducting Hot Electron Bolometer (HEB) receiver currently in operation in Northern Chile has been performed in our laboratory. Using an open waveguide probe, we have mapped both the amplitude and phase of the beam emerging from our 1.5 THz HEB receiver package, across a number of planes along the line of propagation of the radio-beam. With an integration time of about 100 ms per point, a signal-to-noise ratio of about 25 dB was achieved for a beam waist of 3.5 mm. These measurements have proved to be invaluable in achieving good alignment between the cryostat housing the HEB mixer and the remainder of the receiver and telescope optics. The accuracy of our beam measurement is estimated to be ±0.2 mm in position and ±5 arc minutes in angular displacement.**

***Index Terms*—Near-field antenna measurements, vector measurements, submillimeter waves.**

I. Introduction

The vector beam measurement technique developed for the longer submillimeter wavelengths [1,2] is an extremely useful tool in the alignment of high performance superconducting receivers [3]. This method has been demonstrated to work up to a frequency of 1 THz [4]. Recently, we have further extended the frequency range of our Terahertz near-field measurement capability to 1.5 THz.

In this paper, we report the laboratory measurement of the beam pattern of the 1.5 THz superconducting Hot Electron Bolometer (HEB) receiver [5] currently installed in the Receiver Lab Telescope on Cerro Sairecabur, in Northern Chile [6,7]. This receiver employs an HEB mixer based on an NbTiN film. The Local Oscillator (LO) is a cascaded doubler cascade pumped by a 90 GHz power amplifier chain [8]. Our approach is to pre-align the receiver package in our laboratory in Cambridge using the near-field measurement range. These measurements have proved invaluable in achieving good alignment between the cryostat housing the HEB mixer and the remainder of the receiver and telescope optics which include a Martin Puplett diplexer various plane mirrors and focusing elements. This ensures good pointing at telescope and minimizes the amount of operation performed at 5500 meter altitude.

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II. The Transmitter

Following standard near-field measurement techniques, we employ an open waveguide probe in the measurement. This ensures that we are accurately sampling the near field profile, with minimal disturbance on the beam to be measured. The open waveguide probe measures 0.5 x 0.25 mm. It is significantly over-moded at 1.5 THz but since the aperture is much smaller than the size of the beam to be measured, the fundamental waveguide mode should be most efficiently coupled to the receiver beam.

Given that the HEB mixer is quite sensitive, the required transmitter power should be quite small. The following formula gives a reasonable estimate of the required transmitter power, P_t, for a given signal-to-noise ratio, SNR, at the beam center:

$$P_t \sim 2n\, k\, T_n\, B\, R_{\text{area}} * \text{SNR}, \tag{1}$$

where n is the number of double-side-band mixers in the down conversion from 1.5 THz to the final frequency of amplitude and phase measurement; k is the Boltzmann constant; T_n equals the receiver noise temperature plus 300 K (background temperature); B is the noise equivalent bandwidth of the vector measuring instrument; and R_{area} is the ratio of areas between the mean beam size and the probe size. In our measurement set-up n = 2 and $B \sim 10$ Hz for an integration time of 100 ms. The double-side-band receiver noise temperature is about 1500 K. The size of the beam is taken to be πw^2, where w is the beam waist radius at the measurement plane. Depending on the plane of measurement, the area ratio ranges from 80 to 400. For an SNR of 25 dB, the required transmitter power is of the order of 0.1 pW.

A harmonic generator is sufficient to generate such small power. A point contact Schottky barrier multiplier is most suited for this application. We have chosen a multiplier chain consisting of a doubler – tripler cascade originally intended for 650 GHz operation. A high-pass filtering section was inserted between the output of the multiplier and the probe to allow only frequency components higher than 1 THz to be radiated. The multiplier was pumped by a Gunn oscillator operating at around 122 GHz. The measurement frequency of 1.464 THz was the 12^{th} harmonic of the multiplier.

III. Measurement Setup

One key issue in THz vector measurement is that the frequencies of the transmitted signal and the Local Oscillator (LO) have to be perfectly synchronized. Our strategy was to employ a single synthesizer to operate both the transmitter and the THz LO in a homodyne set-up. A block diagram of the measurement set-up is given in Fig. 1. To maintain phase coherency, the secondary LO in the second down converter unit and the reference to the phase-lock unit were derived from direct multiplication from the 10 MHz reference output of the synthesizer.

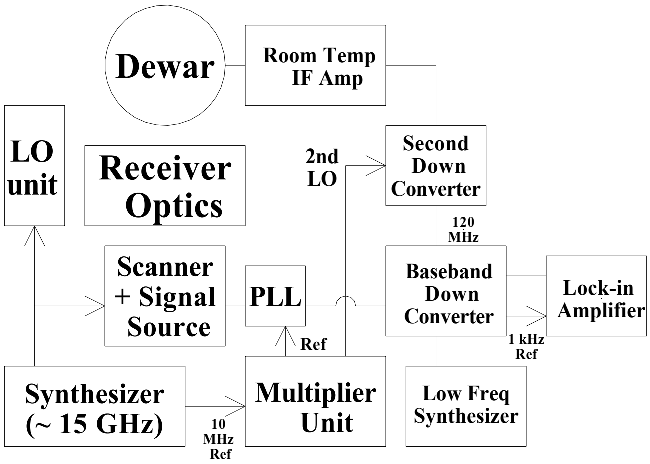

Fig. 1 Block diagram of the Set-up of vector beam measurement at 1.464 THz of HEB receiver.

The THz LO unit consists of a cascade of multipliers and 90 GHz power amplifier modules [8]. The net multiplication factor from the driving synthesizer is 96. Because of this high multiplication ratio, there is considerable amount of phase noise at the output frequency of 1.5 THz, even if we start with a very clean source at 15 GHz. This is especially true for frequency components close to the carrier. Consequently, we have chosen to use a lock-in amplifier instead of the vector voltmeter as the final vector measurement instrument. One advantage of the lock-in amplifier is that it affords very narrow and adjustable noise equivalent detection bandwidth. In contrast, the vector voltmeter offers a noise equivalent bandwidth in excess of 1 kHz. A low frequency synthesizer was used to down convert both the reference and the signal channels to 1 kHz for measurement by the lock-in amplifier. An integration time of 10 ms was used, yielding an equivalent bandwidth of around 100 Hz.

IV. Results of Measurements

A number of scans have been performed along the line of propagation of the THz beam. Depending on the beam size in the plane of scan, the beam pattern was sampled with a step size of 0.25 – 0.5 mm. The amplitude and phase stability of the measurement was monitored by returning the probe to the center of the scan in the middle of every row of the raster scan. In Fig. 2, we plot the variation of the measured amplitude and phase with time over a typical scan of 20 minutes (over a 35 x 35 grid).

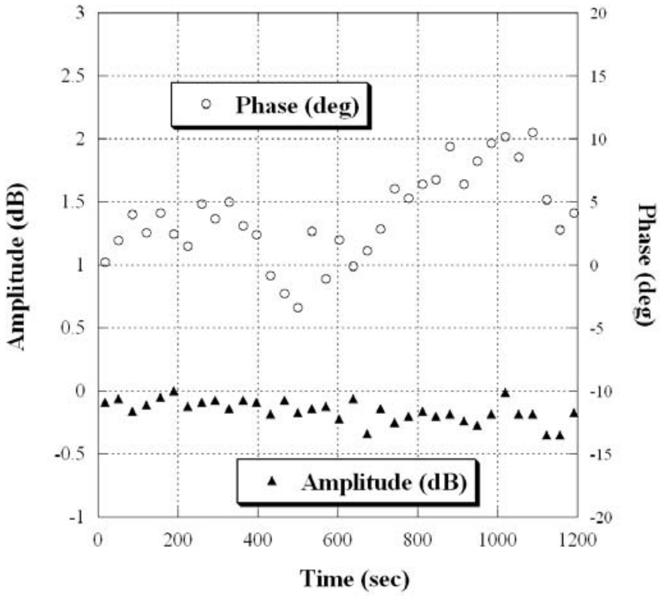

Fig. 2 Measured amplitude and phase fluctuations at 1.464 THz over a 20 minute scan. These values were registered as the probe was returned to the center of the scan area at each row of the raster scan.

Fig. 2 shows that the maximum amplitude fluctuation is better than 0.3 dB and the peak-to-peak phase fluctuation is only 15 degrees over a 20 minute scan. This amazing good performance is attributed to the stability of NbTiN based HEB mixer [9]. It should be noted that in the course of our scan the mixer bias current, which reflects the amount of absorbed LO power hardly moved.

Fig. 3 gives a two-dimension amplitude pattern. A dynamic range of 25 dB was generally attained. This dynamic range could be increased by increasing the integration time. With an integration time of 10 ms, the scan time was dominated by the motion of the stepper motor, plus the time needed to return the probe to origin for calibration at the middle of each row. Therefore, small increase in integration time would not need to excessive increase in scan time. Note that a settling time equal to 10 times the integration time was built in at each measurement point to allow the lock-in amplifier to settle. Our dynamic range is, however, limited by cross-talk between the reference and measurement channels, generated in the base-band down converter. A more sophisticated circuit is needed.

V. Extraction of Beam Parameters

The position of the beam and its tilt angles with respect to the normal of the plane of scanning are extracted by fitting to the fundamental Gaussian beam:

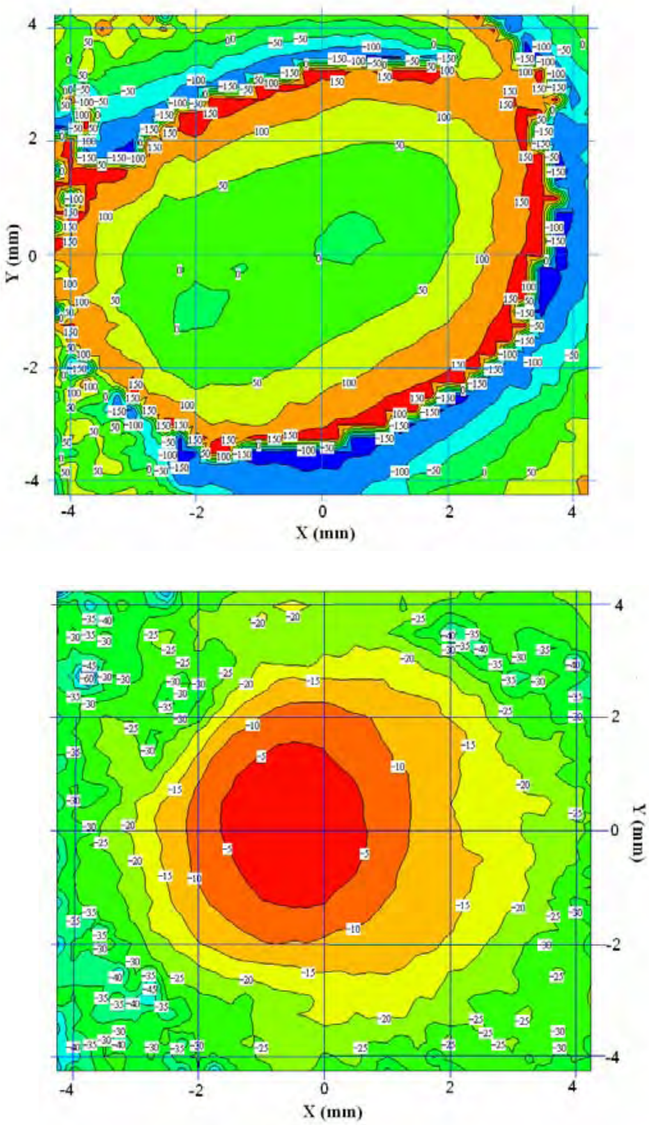

Fig. 3 Two dimensional phase (top) and amplitude (bottom) beam map of the 1.5 THz HEB receiver. The phase contours are labeled in degrees and the amplitude contours are labeled in dB. The asymmetry of the beam pattern is caused by the presence of two 90-degree off-axis parabolic mirrors in the optics train.

$$\Psi(x',y') = \sqrt{\frac{2}{\pi}\frac{1}{w}} \exp(-\frac{x'^2+y'^2}{w^2}) \exp\left[j\beta_0\left(\frac{x'^2+y'^2}{2R} + \delta_x x' + \delta_y y'\right)\right] \quad (2)$$

where $x' = x - x_c$ and $y' = y - y_c$. x, y are scan coordinates. x_c and y_c are the coordinates of the amplitude center of the beam, w is the beam waist radius, R is the radius of curvature of the phase front, and δ_x and δ_y are the angles (in radians) of tilt of the beam with respect to the normal to the scan plane. The beam parameter set of (x_c , y_c , w, R, δ_x , δ_y) is obtained by optimizing the power coupling coefficient:

$$O(x_c, y_c, w, R, \delta_x, \delta_y) = \frac{\iint E_{meas}(x,y)\,\Psi^*_{00}(x,y)\,dx\,dy}{\iint E_{meas}(x,y)\,E^*_{meas}(x,y)\,dx\,dy} \quad (3)$$

For the beam pattern given in Fig. 3, the optimal power coupling coefficient is 88.6%. The coordinates of the beam center are (-0.32, 0.05), with a beam waist radius of 1.9 mm and a radius of phase curvature of 75 mm. The beam tilt angles are 5.2 arc minutes and 3 arc minutes along the x and y axes respectively.

VI. Reliability of Phase Measurement

The challenge of vector near-field measurement at THz frequencies is the reliability of phase measurement. Since there are considerable amount of cabling in the measurement system, any temperature change can alter the measured phase. At 1.5 THz, a 0.4 μm change in cable length would introduce a 1 degree measurement error in phase. Furthermore, the transmitter is linked to the synthesizer through a flexible cable which moves with the scanner. This cable is likely to introduce phase distortion into the measured phase map.

In order to counteract these effects, we have adopted a few counter-measures. First, the synthesizer was first connected to a power splitter and then linked to the transmitter by a 0.9 m phase stable cable. Next, an identical cable was employed to link the second port of the above splitter to the LO unit. Any phase change caused by temperature changes would, therefore, be canceled out. Finally, the cable was bent into a U-shape. Because of our small area of scan (5 x 5 mm), the radius of curvature of our cable does not change appreciably. For larger scan areas, a longer cable may be necessary.

In order to check the reliability of our measurements, we have performed a series of scans in a number of planes along the direction of propagation of the THz beam (*Z*-axis) emerging from the receiver package. For each of these data sets, we extract the beam centers. Beam tilt angles are derived by fitting a pair of straight lines to the *x*- and *y*- coordinates of the beam centers. The results are summarized in Fig. 4.

From the plot, we can deduce that we can determine the position of the beam center to an accuracy of about 0.2 mm. for a beam waist radius of a few mm. The slopes of the fitted lines give us an added measure of the beam tilt angle. This method does not depend so much on the phase measurement. It can. Therefore, be used to check the extracted beam tilt angles which depend critically on the measured phase front of the beam. Table 1 gives the comparison between the extracted beam tilt angles (in radians) in each plane, their average values and the values derived from the slopes of the fitted lines in Fig. 4.

From these data, we can conclude that the standard deviation of the extracted beam tilt angles about their mean is better than 2 milli-radians (~7 arc minutes) and they agree with the amplitude-based method to about 1 milli-radian (~3.5 arc minutes). This confirms the reliability of our phase measurements.

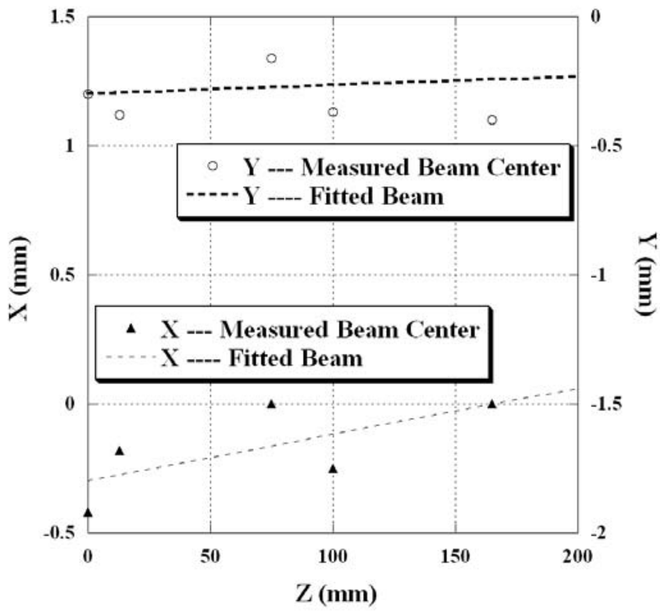

Fig. 4 Propagation of the beam along the Z-axis. The markers give the *x*- and *y*- coordinates of the fitted beam centers from the measured data. The 2 sets of data are fitted by 2 straight lines. The slopes of these lines, +0.0018 and +0.00035 for the *x*- and *y*- data set respectively, give the beam tilt angles in radians.

Z (mm)	0	13	75	100	165	Aver-age	From Fig. 4
1000*δ*x*	-0.90	0.35	-0.70	3.10	3.10	1.00	1.80
1000*δ*y*	-0.60	-1.20	0.70	0.10	0.10	-0.20	0.35

Table 1 Extracted beam tilt angles (given in milli-radians) in different scan planes along the *Z*-axis. These values are compared to their average values and the beam tilt derived from the slopes of the fitted lines in Fig. 4.

VII. Conclusion

Near-field vector beam measurements have been performed successfully at 1.464 THz. A dynamic range of 25 dB has been achieved and the measured data demonstrates good stability, with very low amplitude and phase drifts. By fitting to the fundamental Gaussian beam, we were able to extract the beam center coordinates, beam waist radius and the beam tilt angles. These measurements allow us to determine beam displacement to an accuracy of 0.2 mm and beam tilt angles of 5 arc minutes. We have also established that near-field phase measurements are highly reliable even at 1.5 THz. Finally, this technique is a key step in the alignment and operation of the 1.5 THz HEB receiver currently installed in Northern Chile.

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