Near Field Vector Beam Measurements at 1 THz

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***Abstract*—We have performed near-field vector beam measurements at 1.03 THz to characterize and align the receiver optics of a superconducting receiver. The signal source is a harmonic generator mounted on an X-Y translation stage. We model the measured two-dimensional complex beam pattern by a fundamental Gaussian mode, from which we derive the position of the beam center, the beam radius and the direction of propagation. By performing scans in the planes separated by 400 mm, we have confirmed that our beam pattern measurements are highly reliable.**

***Index Terms*—Antenna pattern, Gaussian beam, submillimeter wave, vector measurements.**

I. INTRODUCTION

NEAR-FIELD measurements at millimeter wavelengths are now widely used to characterize and align beam waveguide systems, which link transmitting or receiving modules to reflector antennas. Based on well-established microwave near-field measurement techniques, we have pioneered a near-field vector measurement system for use at sub-millimeter wavelengths [1], [2]. This system is now routinely used for the alignment of the receiver optics of the 200, 300, and 600 GHz superconducting receivers installed in the Submillimeter Array, a radio interferometer of six 6-m antennas, designed and operated by the Smithsonian Astrophysical Observatory on the summit of Mauna Kea, Hawaii [3].

At higher frequencies, vector measurements are more challenging because of the reduced wavelength. For example, 1 μm change in the length of the reference cable in a typical measurement system leads to a phase change of 1.5° at 1 THz, and large phase errors resulting from temperature fluctuations can occur. In addition, flexing of the cable linking the scanning waveguide probe to the measurement equipment adds to the phase uncertainty. Finally, receiver technology at THz frequencies is still immature and many THz receivers do not even have good amplitude stability.

We refined our measurement set-up to characterize the receiver optics of a superconducting Niobium Nitride Hot-Electron Bolometer (HEB) mixer receiver [4] to be installed in an 80 cm Terahertz telescope in Northern Chile [5], and report here on the first successful near-field vector beam measurement made at 1 THz.

II. MEASUREMENT SET-UP

A block diagram of the measurement set-up is given in Fig. 1. The transmitter, mounted on an X-Y translation stage, consists of an 85.68 GHz Gunn oscillator followed by a varactor frequency tripler and a harmonic generator with a 0.5 $\times$ 0.25 mm open-ended waveguide probe at the output. The signal frequency is the 4th harmonic at 1.028 16 THz. The transmitter assembly is covered by a sheet of AN-72 microwave absorber, except for a small opening for the waveguide probe. We typically use a scan area of 50 $\times$ 50 mm, with a step size of 0.5–0.8 mm. The transmitter is linked to the other part of the measurement system through a 1 m long phase-stable cable. From microwave measurements, we expect that this cable will introduce an RMS phase error of 15° at 1 THz due to the scanning motion.

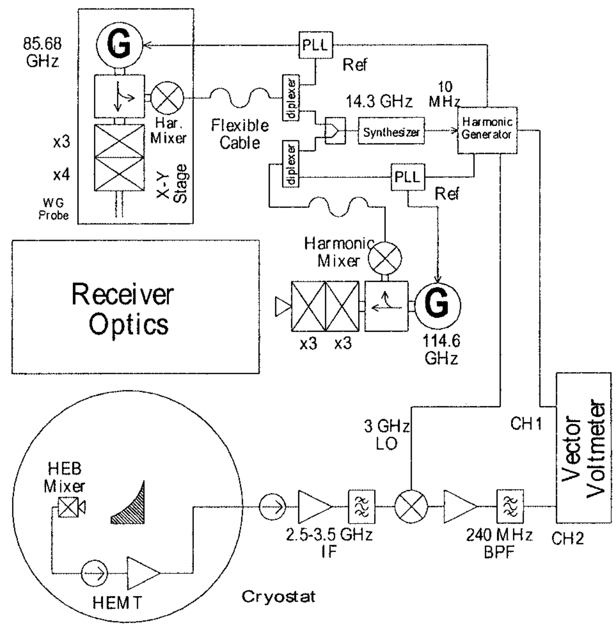

Fig. 1. Schematic of the Set-Up of Vector Beam Measurements at 1.028 16 THz. The signal source is mounted on a computer controlled X-Y translation stage, which can scan over an area 150 $\times$ 150 mm. Inside the cryostat, the HEB mixer block is equipped with a corrugated horn illuminating an off-axis parabolic mirror. The receiver optics in front of the cryostat consists of a Martin-Puplett interferometer for LO/signal diplexing and an off-axis parabolic mirror for refocusing the beam from the cryostat. The scanning waveguide probe is nominally located at about 1 m from the cryostat window. The object of the measurements is to ensure that all the optical components are well aligned.

The Local Oscillator (LO) unit consists of a 114.6 GHz Gunn oscillator followed by a cascade of two frequency triplers, giving an LO frequency of 1.0314 THz. Both the transmitting and LO Gunn oscillators are phase-locked to a single microwave reference at 14.3 GHz, but on different sidebands. This results in a simple system with maximum phase coherence. The IF, at 3.24 GHz, is mixed with a 3 GHz second LO to produce a 240 MHz signal, which is passed to a vector voltmeter that measures both amplitude and phase. All the RF references used in our system are harmonically generated from a 10 MHz master reference.

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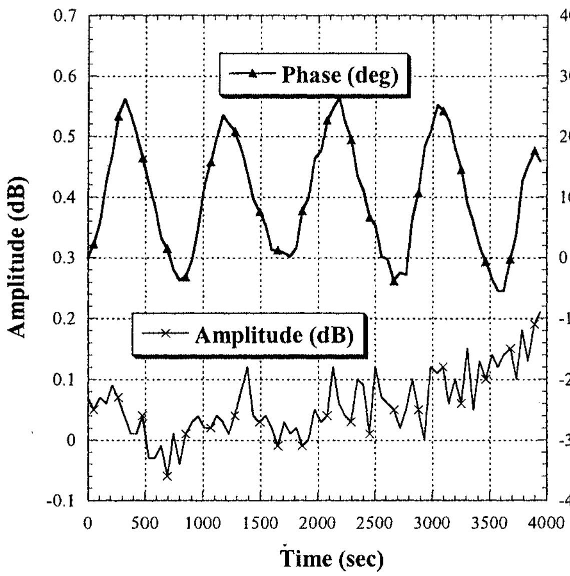

Fig. 2. Measured amplitude and phase fluctuations of our beam measurements system over a period of 4000 seconds. The measured phase shows a periodicity of about 800 s. This can be attributed to the temperature change in the laboratory where the air-conditioning units cycles every 15 min.

III. Results of Measurements

We can achieve a dynamic range in excess of 40 dB with our measurement scheme. However, to avoid saturation of the HEB mixer, we generally limit the transmitter power to give only 40 dB dynamic range. With a double-side-band noise temperature of about 1400 K and a measurement bandwidth of 1.3 kHz, the actual signal power incident to the receiver at the beam center is around 1 nW, which is much smaller than the estimated 100 nW of LO power absorbed by the HEB mixer element.

The measured data exhibit good phase stability with short-term phase fluctuations of only $\pm 2^\circ$ in 1 min. When the phase lock loops of the Gunn oscillators are correctly adjusted, the system exhibits remarkably low long-term amplitude and phase fluctuations. Fig. 2 plots the variation of measured amplitude and phase with time. In this test, the probe is set at the beam center. From the figure, we observe that the phase fluctuation is below 20° over 4000 s while amplitude fluctuations remain below 0.1 dB. These long-term phase fluctuation is corrected by frequent calibration at the center of the scan area during the raster scan.

With this set-up, the scans are also highly repeatable. Two scans, taken on 2 successive days show an RMS amplitude difference of about 0.05 dB and an RMS phase difference of about 4° over the entire scan area. Fig. 3 shows a measured 2-D amplitude beam pattern. Because the measured beam is paraxial, no probe correction is used.

IV. Beam Fitting

The complex beam is modeled by a fundamental mode Gaussian beam [6]

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

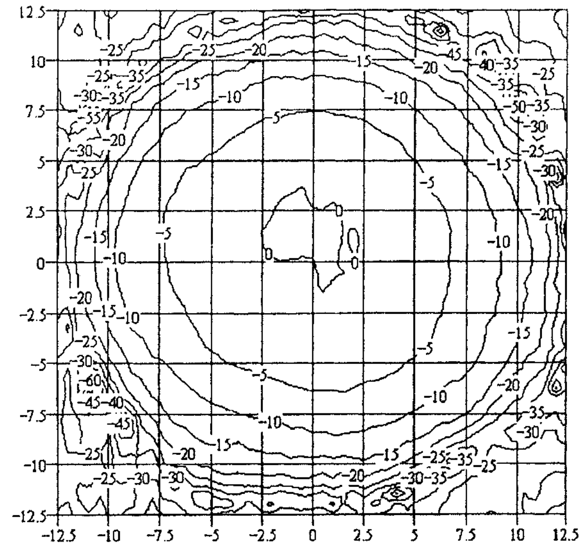

Fig. 3. Two-dimensional amplitude pattern measured by the THz near-field scanner. The contours are in dB and the X- and Y-axis are labeled in mm. This beam pattern fits well to a fundamental Gaussian beam mode with $w = 7.4$ mm (refer to Table I Plane 1). The signal-to-noise ratio at the beam center is 40 dB. From the shape of the contours, we can infer that residual reflections from the measurements set-up are below -20 dB level.

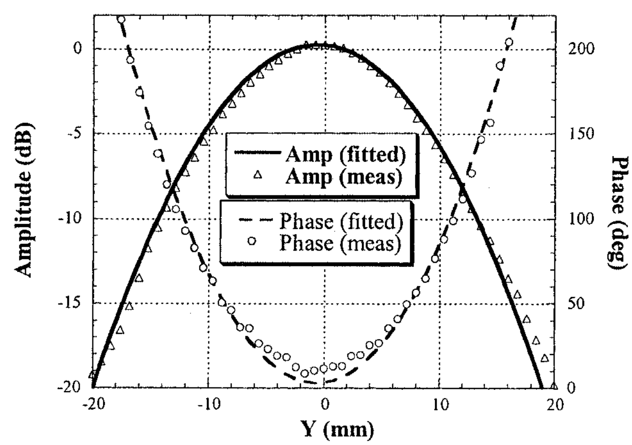

Fig. 4. E-plane cuts of complex beam pattern, showing measured amplitude and phase, along with the best-fit fundamental mode. Gaussian beam: $w = 12.8$ mm and $R = 842$ mm (refer to Table I Plane 2).

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 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. By optimizing the power coupling coefficient to the fundamental Gaussian mode, we can derive the best fit parameter set of (x_c, y_c, w, R, δ_x, δ_y) for the measured beam. This procedure allows us to check if the beam is well behaved. In our experiments, we obtain a power coupling coefficient of typically 0.97 to the fundamental Gaussian mode. Fig. 4 shows a 1-D cut of the radiation pattern for both the measured and fitted beam. It can be seen that the data fitting is very good. From repeated scans of the same beam, we infer that the fitted beam displacement and beam radius are accurate to ± 0.2 mm, the radius of curvature has a 1% accuracy, and the tilt angles δ_x and δ_y are determined to within $\pm 3 \times 10^{-4}$.

TABLE I
SUMMARY OF PARAMETERS OF BEST-FIT FUNDAMENTAL MODE GAUSSIAN BEAM FOR TWO NEAR-FIELD SCANS TAKEN IN TWO PARALLEL PLANES 400 mm APART. ALL DIMENSIONS ARE IN mm, EXCEPT FOR THE TILT ANGLES δ_x AND δ_y

	x_c	y_c	w	R	δ_x	δ_y	w_0	Z_w
Plane 1 ($z = 0$)	-0.5	-0.1	7.35	672	-3.6×10^{-3}	$+1.0\times10^{-3}$	5.55	-289
Plane 2 ($z = 400$)	-2.1	0.1	12.8	842	-3.7×10^{-3}	$+0.9\times10^{-3}$	5.52	-284

Using the derived value of w and R, we can also derive the beam waist radius w_0 and the distance of the beam waist from the scan plane, Z_w.

The main issue of vector beam measurement at 1 THz is the reliability of the phase measurements. In order to verify our measurements, we have performed scans at two planes, separated by 400 mm along the axis of propagation of the beam. Table I summarizes the data from a pair of scans. From the amplitude beam centers in the 2 planes, we can derive the beam tilt angles independently without using the phase distribution. This gives tilt angles of -4×10^{-3} and $+0.5 \times 10^{-3}$ for the x and y directions respectively, which agree well with the values of δ_x and δ_y derived from the phase data of the 2 scans. The beam waist radius, w_0, and its position, Z_w also show remarkable agreement.

V. CONCLUSION

We have performed near-field vector beam measurements at 1 THz. Our measurement system is very robust and scan data are highly repeatable. These measurements allow us to determine beam displacement to an accuracy of 0.2 mm in x- and y-axes, and beam tilt angles to an accuracy of 3×10^{-4}. The phase measurements are proved to be highly reliable. This technique offers us an effective way to verify and align the beam waveguide system of receiver systems operating at 1 THz.

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