Characterization of an integrated lens antenna at terahertz frequencies

P. Yagoubov, W.-J. Vreeling, P. de Korte

Sensor Research and Technology Division
Space Research Organization Netherlands
Postbus 800, 9700 Groningen, The Netherlands

Abstract

Results of beam pattern and polarization measurements on quasioptical integrated lens antennae at terahertz frequencies are presented. The integrated antenna consists of a planar spiral antenna mounted on the flat surface of an extended hemispherical lens. The planar antenna used is an equiangular logarithmic spiral, which comprises 1.5 turns with a spiral expansion rate of 3.2 per turn. The RF bandwidth of the antenna is designed to 0.3-2.5 THz. We have investigated the optical performance of such an integrated antenna and observed that the polarization is changing from almost circular at frequencies below 1.4 THz to elliptical with an axial ratio equal to 3 at 2.5 THz. The beam patterns have been measured up to 2.5 THz for two orthogonal polarization directions aligned with the elliptical polarization axes. The main lobes are primarily diffraction limited by the aperture of the lens. The first order sidelobe level equals -16 dB at 0.6 THz and increases to –8-12 dB at 1.4 THz and -7-10 dB at 2.5 THz.

Introduction

Properties of the receiver antenna play a very important role in the overall coupling efficiency of the detector to the incoming signal and have to be carefully optimized. In the millimeter wave region the best antenna performance is obtained with the waveguide technology. However for terahertz frequencies the waveguide fabrication becomes difficult and costly, while its losses also increase with frequency. An alternative approach is a quasioptical planar antenna lens combination [1]. It was theoretically shown that the best coupling to the incoming Gaussian beam is obtained when the planar antenna is placed on the backside of the hyperhemispherical lens [2]. However, many research groups developing prototype quasioptical receivers for the submillimeter wavelength prefer to use elliptical lens (EL) instead. This is because the hyperhemispherical lens antenna requires a small f-number lens in front of the receiver causing additional loss in the signal path. If the planar antenna is placed at the distant focus of the EL, the Gaussian beam coupling efficiency is about 10% worse than in case of the hyperhemispherical lens, but the resulting beam pattern is very narrow since it is diffraction limited by the aperture of the lens. The system is then compatible with large f-number optics. The synthesized elliptical lens (SEL), which is in fact an extended hemispherical lens with an extension equal to 0.39 the lens radius (in case of Si), has been shown to be a good approximation of the EL case [2]. The calculated Gaussicity and reflection loss at the lens-air interface for the SEL and EL are basically the same. The difference is only in the directivity, which is larger with the EL, but the sidelobe level is slightly higher in this case as well.

Different types of planar antennas have been successfully used in combination with extended hemispherical and EL. Because of the diffraction limit, the far-field of the integrated antenna based on EL or SEL is primarily determined by the size of the lens. So the main difference between the beam patterns of various antennae are the side-lobe level and the polarization. It has been demonstrated that double-slot antennas have superior performance in case both low side-lobe level and cross-polarization are required. The first sidelobe level of the twin slot antenna EL combination is measured between –15 to –18 dB at frequencies up to 1 THz [3] and -10 dB at 2.5 THz [4]. Recently the measurements of the beam pattern have been done at 2.5 THz also with the spiral antenna SEL combination [6]. The 1-D pattern is obtained with the symmetric sidelobe level of about –8 dB. However, the pattern was measured only in the E-plane of the source and no results on the polarization were reported.

It is beyond discussion that receivers designed for operation at a telescope must have the best possible coupling efficiency to the single mode Gaussian beam and have low cross-polarization level. Thus the antenna polarization, beampattern profile, sidelobe level, loss etc. play a crucial role in the final receiver performance. However, during the development stage of a specific type of mixer, most of the heterodyne measurements in the laboratory do not require perfect coupling to a Gaussian beam and beam pattern, side lobe and polarization characteristics are only of secondary importance. For instance, to determine the receiver noise temperature, the Y-factor technique with the blackbody loads as signal sources is typically used. Since blackbodies are multi-modal sources all components of the receiver beam pattern, which are not blocked by the aperture of the input window or a beamsplitter, will be fully coupled to the signal. So for mixer development purposes broad frequency antennae, like logarithmic spirals, are frequently used given the advantage of multi-frequency measurements at one and the same mixer.

In this paper we investigate the performance of an integrated antenna system based on the logarithmic spiral antenna and a SEL for frequencies up to 2.5 THz. The device is a NbN Hot Electron Bolometer (HEB), originally designed as a mixer for submillimeter wavelength [5]. Historically a spiral antenna has been chosen as a receiving antenna for the HEB mixer development due to its wide bandwidth. The spiral antenna belongs to a class of so-called frequency independent antennas, thus allowing one to perform all tests with one selected device in a wide spectral range. This was an important issue because the HEB mixers are aimed to be used at terahertz frequencies and thus have to be finally tested there. At frequencies below 1 THz, however, the mixer evaluation and optimization in the laboratory is appreciably easier, given the availability of stable LO sources, like Backward Wave Oscillators (BWOs) or Gunn-multiplier chains. In addition, some of the measurements, like the intermediate frequency (IF) roll-off determination, can only be done at frequencies below 1 THz, where frequency tunable sources are available. Above 1.5 THz frequency only a CO_2 pumped far-infrared (FIR) laser system is currently an option to deliver sufficient amount of power. This only allows for a limited number of discrete lines and stability is more difficult obtained. Obviously, the results on mixer noise and gain variations at various frequencies give additional information for the further analysis and better understanding of the device physics.

Antenna design

The planar antenna is an equiangular spiral with a 90° arm width yielding a self-complementary design. This implies that the antenna impedance should be purely real and equal to 75 Ohm for the antenna on a Si substrate [7]. The spiral structure of the antennas extends 1.5 turns and the spiral expansion rate is 3.2 per turn. A photo of the final device is shown in the Fig. 1.

The total antenna arm length, calculated from its radii and the expansion rate, is about 300 μm. Setting this equal to a maximum effective wavelength yields a lower cutoff frequency for the antenna of 300 GHz in free space. The higher cutoff frequency of the antenna is defined [8] as the frequency at which the antenna polarization changes from circular to elliptical with an axial ratio of 2. This frequency depends on the construction precision of the antenna feed. Since the spiral arms naturally converge to a point, one has to terminate the center in a tapered section, see Fig. 1. According to [8] the cut-off frequency is set by the length of the tapered section, since it equals about half the cut-off effective wavelength. This length is roughly 20 μm for the spiral used in this paper, setting the upper frequency limit to 2.2 THz. The axial ratio of elliptical polarization increases towards higher frequencies until the polarization becomes linear. This happens when the tapered section is equal to the effective wavelength and the antenna starts to act as a dipole. The impedance and the beam pattern of the antenna are expected to have wider than the polarization bandwidth so that the antenna can still work efficiently although the polarization is not circular.

The bolometer is located between the antenna arms, as shown in the Fig. 1. The chip is placed on the backside of the lens, as shown in Fig. 2. The lens is a SEL with a diameter of 10 mm, made from a high resistivity Si. The extension length (the distance from the geometrical center of the sphere to the antenna) is 1.95 mm. No antireflection coating is applied yet to the lens curved surface to reduce the reflection loss.

Polarization

The polarization of the antenna has been measured at two frequencies: 1.4 THz and 2.5 THz. The schematic of the setup is shown in the Fig. 3. The 1.4 THz source is a Schottky diode based tripler fed by a 465 GHz carcinotron. For the 2.5 THz we use a CO_2 pumped far infrared (FIR) ring laser. The first grid is used to define the polarization of the source and is fixed. The two other grids are rotated independently during the measurements, each by 180 degrees in steps of 15 degrees. The RF power is modulated with a 35 Hz mechanical chopper. The HEB is biased with a constant voltage source and the current change, due to the incident power modulation, is monitored by a lock-in amplifier. The bolometer is operated in a linear regime, which was checked beforehand by means of polarizing grids as attenuators.

The experimental data were compared to the calculated transmission through the system of three grids and a modeled coupling to the antenna. We assumed a general case of elliptical polarization of the antenna with the axial ratio α. α has been defined as the ratio of amplitudes of the electrical field along the long and short axis of the ellipse. Thus $\alpha=1$ corresponds to the circular polarization of the antenna, whereas $\alpha=\infty$ to the linear one. The second parameter in the calculations is angle φ, which we define as the angle between the line along the tapered section of the antenna and the long axis of the ellipse.

The polarization was found to be elliptical at both frequencies, although closer to the circular at 1.4 THz ($\alpha=1.3$), and strongly elliptical at 2.5 THz, with $\alpha=3$. φ equals about -25 degrees. This means that the long axis of the ellipse is *25* degrees counterclockwise from the direction of the tapered section in the antenna center, as shown in Fig. 1.

The results on the antenna polarization at 2.5 THz disagrees slightly with that reported in [8], where the case of elliptical polarization of the spiral antenna with $\alpha=2$ happens at a frequency where the length of the tapered section is equal to the effective half-wavelength. In our case the length of the tapered portion is about the half-wavelength but the axial ratio is 3 instead of 2. This is an indication that in this case the center part of the antenna has a larger influence on the polarization.

It is useful to compare the results of the polarization measurements with those reported in [9]. The antenna design in [9] is very similar to the one we use here, but all the dimensions of the antenna, including the size of the tapered section, are scaled down by a factor of 3. If we assume that just the size of the tapered section is important, and basing on our result $\alpha=1.5$ at 1.4 THz, we would expect to have $\alpha=1.5$ at 4.2 THz with the 3 times smaller antenna. However, the authors of [8] reported the larger axial ratio of 1.7 already at 2.5 THz [10]. This is also an indication of the fact that α tends to increase much faster with frequency than one could expect from the antenna geometry alone. We do not have a solid explanation for this yet. One of the thinkable reasons is an increase with frequency of the surface resistance of Au forming the antenna arms. This resistive loss may cause the field to decay faster along the antenna arms and therefore make the influence of the antenna center larger. The size and geometry of the bolometer in the antenna center as well as a possible mismatch between them are obviously also very important and could modify the radiation properties of the antenna.

Beam pattern measurements

Far-field beam pattern measurements have been done at three frequencies: 0.6 THz, 1.4 THz and 2.5 THz in an experimental setup similar to that shown in the Fig. 3. The submillimeter source at 0.6 THz is a BWO. The dewar is placed on a rotation/tilt table to allow for the angular measurements. The tilt movement will be referred to as the vertical scan and the rotation as the horizontal scan. The angle resolution of the system is 0.1°. The integrated antenna is located in the center of rotation. The measured beam pattern of the antenna is therefore expected to be independent of the beam pattern of the signal source. There are no focusing elements between the signal source and the detector and the distance between them is 70-100 cm. By using two grids, the polarization of the incoming signal is set either vertical or horizontal. The antenna is positioned in the dewar in such a way that the direction of the long axis of the polarization ellipse (see Fig. 1) is close to vertical.

Let us start discussion with the 0.6 THz measurements. The beam pattern profiles at this frequency are very similar for both polarizations and scans. A typical result is shown in the Fig. 4. The pattern is symmetric with the first sidelobe level of -16 dB. It is worth noticing that this is close to the theoretically predicted diffraction pattern and similar to the patterns measured with the double slot or double dipole antennas at these frequencies. The full width half maximum (FWHM) is 3.47°.

The results of the measurements at 1.4 THz are shown in the Fig. 5. The patterns are still pretty symmetric relative to the boresight but noticeably different for the horizontal and vertical scans. The FWHM is 1.7° for the horizontal scan and 1.4° for the vertical one. There is no big influence of the polarization on the beamwidth and side-lobe positions within one scan direction but the sidelobe levels are polarization dependent.

Similar patterns are observed at 2.5 THz, see Fig. 6. The FWHM here is about 1° for the horizontal scan and 0.7°-0.9° for the vertical. We have also made a 2-D scan of the antenna pattern at 2.5 THz and the result is shown in the Fig. 7.

To summarize the data, we established that the width of the main lobe scales with the frequency, and is close to the expected diffraction limit of the lens aperture. The asymmetric beam patterns at high frequencies for the different scans may be attributed to the variation of the planar antenna pattern. A significant change of the shape and the phase of the antenna pattern may also explain the increase of the sidelobe level with frequency. However, there might be other reasons for this as well. For instance, a displacement of the planar antenna has a frequency dependent effect on the beampattern of the integrated antenna.

Conclusions

We have tested the integrated lens antenna, a logarithmic spiral in combination with a SEL, in a wide frequency range from 0.6 THz to 2.5 THz and have found that the polarization is changing from almost circular at relatively low frequencies to elliptical with an axial ratio of 3 at 2.5 THz. The far-field pattern of the antenna has been measured. The sidelobe level increases towards higher frequencies. However, due to the diffraction limit the beam pattern becomes narrower at higher frequencies. The total width of the main lobe and the first sidelobes is about 4 degrees at 2.5 THz. Since most of the power is contained within this angle, we can expect that this antenna couples efficiently with a multimode source and is a good choice for prototype mixers to evaluate in the laboratory.

Acknowledgments

The authors are thankful to A. Baryshev, H. van de Stadt, W. Ganzevles and D. Nguyen for the useful discussions and assistance in the measurements. M Kroug is acknowledged for the fabrication of the device.

References

[1] D.B.Rutledge and M.Muha, "Imaging antenna arrays," IEEE Trans. Antennas Propagat, vol. 30, pp. 535-540, 1982

[2] D.F.Filipovic, S.S.Gearhart, and G.M.Rebeiz, "Double-slot antennas on extended hemispherical and elliptical silicon dielectric lenses," IEEE Trans. Microwave Theory Tech., vol. 41, pp. 1738-1749, 1993

[3] A.M.Baryshev, B.D.Jackson, G.deLange, S.V.Shitov, N.Iosad, J.R.Gao, T.M.Klapwijk, ”Quasi-Optical Terahertz Mixer”, Proceedings of the 11th Int. Symp. on Space Terahertz Technology, The University of Michigan, Ann Arbor MI, 149, 2000

[4] R. Wyss, B. Karasik, W. McGrath, B. Bumble, H. LeDuc, “Noise and Bandwidth Measurements Of Diffusion-Cooled Nb Hot-Electron Bolometer Mixers at Frequencies Above the Superconductive Energy Gap”, Proceedings of the 10th Int. Symp. on Space Terahertz Technology, Charlottesville, VA, 214, 1999

[5] P. Yagoubov, M. Kroug, H. Merkel, E. Kollberg, G. Gol’tsman, S. Svechnikov and E. Gershenzon, “Noise temperature and local oscillator power requirement of NbN phonon-cooled hot electron bolometric mixers at Terahertz frequencies”, *Appl. Phys. Lett.*, 73, 2814, 1998

[6] H.-W.Hübers, A.Semenov, J.Schubert, G. Gol'tsman, B.Voronov, E.Gershenzon, "Performance of the Phonon-Cooled Hot-Electron Bolometric Mixer between 0.7 THz and 5.2 THz", Proceedings of the THz Electronics Conference, Darmstadt, September 2000

[7] S.S. Gearhart, J.Hesler, W.L.Bishop, T.W.Crowe, and G.M.Rebeiz, "A Wide-band 760-GHz Planar Integrated Schottky Receiver," IEEE Microwave and Guided Wave Lett., vol. 3, pp. 205-297, 1993

[8] J.D.Dyson, "The Equiangular Spiral Antenna," IRE Trans. Antennas Propagat., pp. 181-187, April 1959

[9] P. Yagoubov, M. Kroug, H. Merkel, E. Kollberg, J. Schubert, H.-W. Huebers, G. Schwaab, G. Gol'tsman, and E. Gershenzon, "NbN Hot Electron Bolometric Mixers at Frequencies Between 0.7 and 3.1 THz", *Proc. 10th Int. Symp. on Space Terahertz Technology*, Charlottesville, VA, 214, 1999

[10] The axial ratio in [9] is defined as the ratio of powers. To compare the result with ours we took a square root of the number reported there.

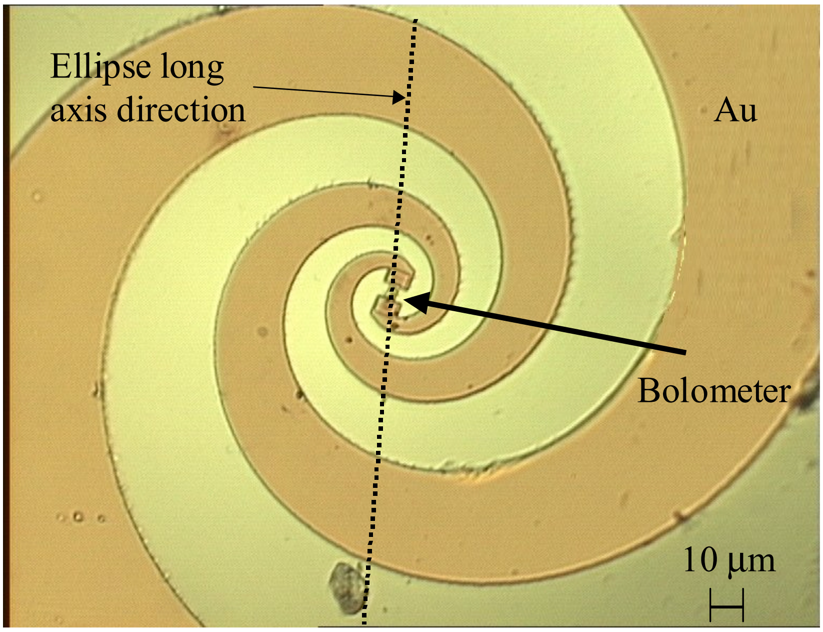


Figure 1. Micrograph of the device. The antenna is a planar spiral made from Au. The darker area is Au. The HEB bolometer is at the center of the spiral arms. The dotted line shows the measured direction of the long axis of the polarization ellipse.

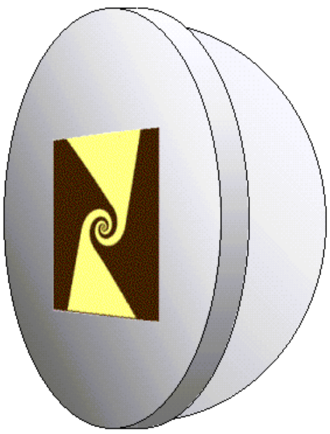


Figure 2. Schematic of the antenna – lens combination.

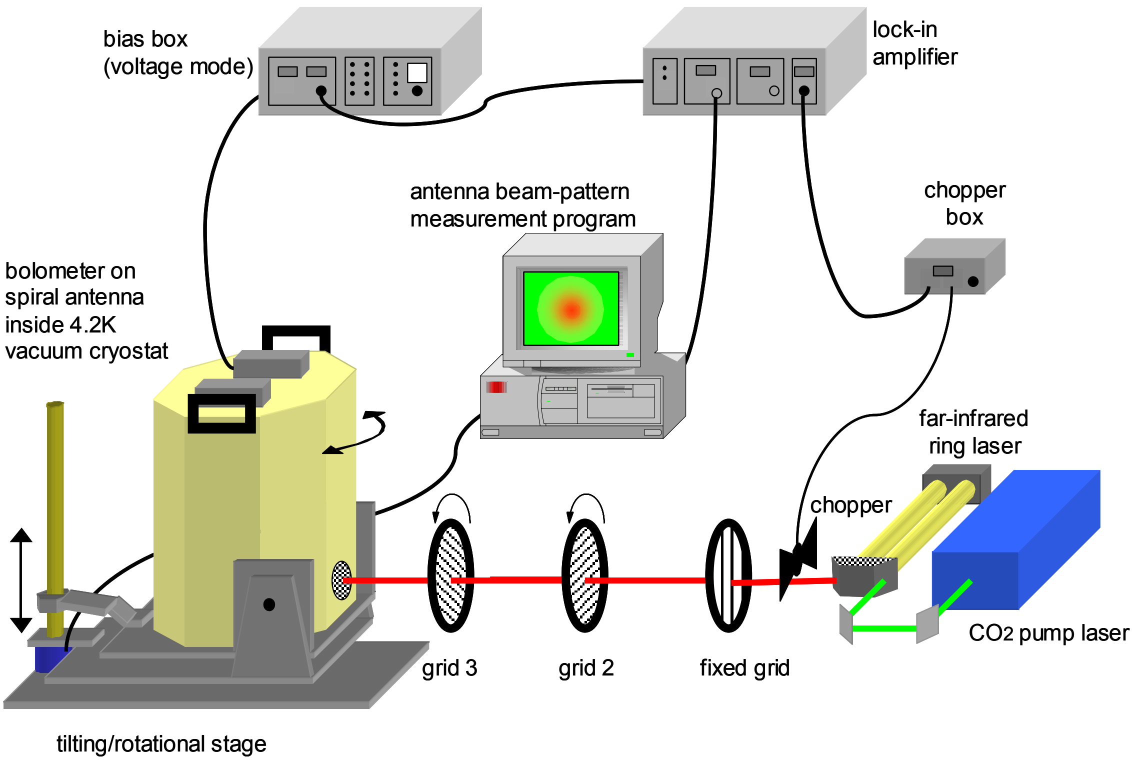


Figure 3. Schematic drawing of the measurement setup. Three submillimeter sources are used for the measurement of polarization and far-field beam pattern, i.e. a BWO at 0.6 THz, a carcinotron + tripler at 1.4 THz, and a CO2 pumped FIR laser at 2.5 THz. Only the laser is shown here.

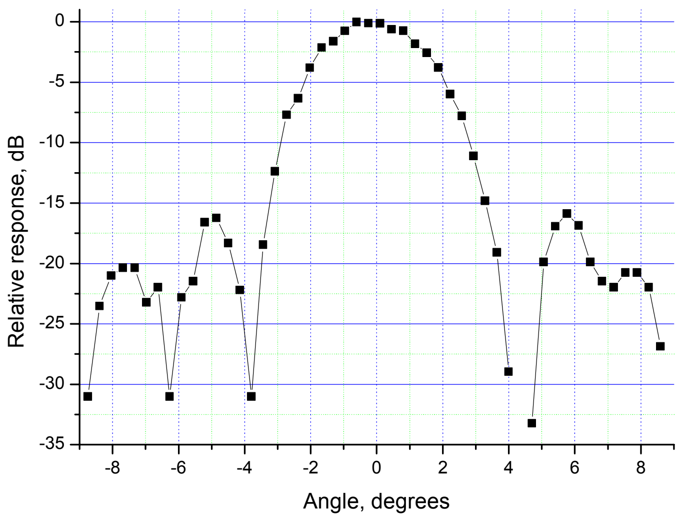
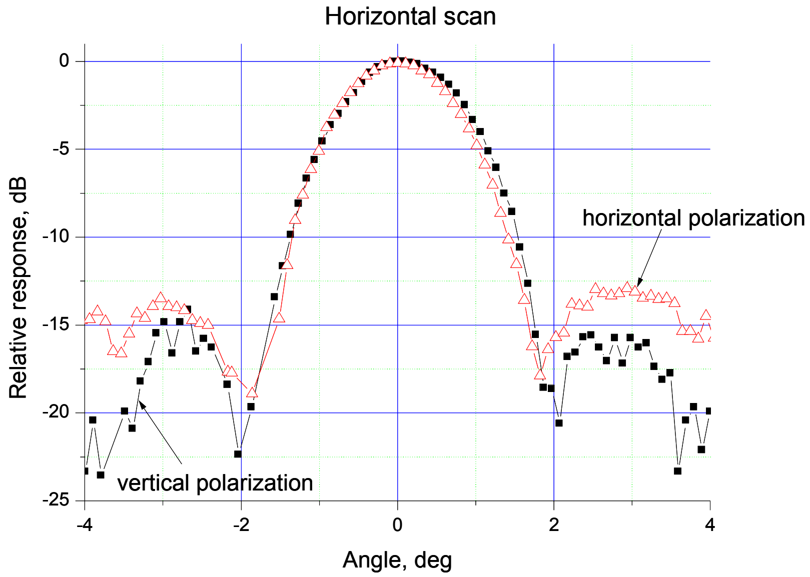


Figure 4. The measured beam pattern of the integrated antenna at 0.6 THz. Symbols are the measurement points, the solid line is a guide for eye.

a)



b)

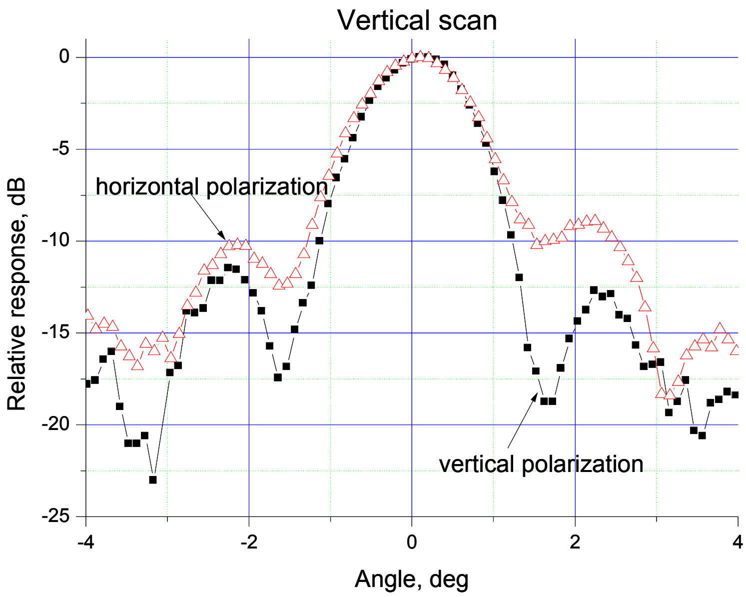
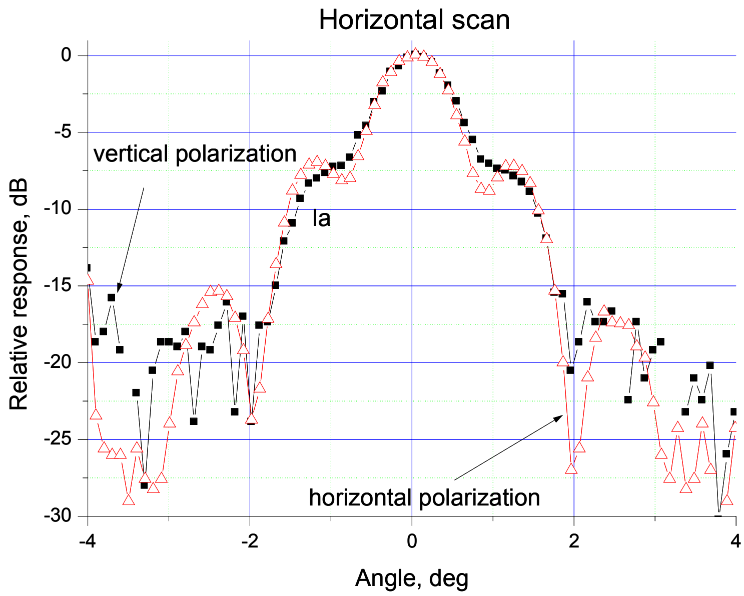


Figure 5. The measured beam pattern of the integrated antenna at 1.4 THz. The horizontal scan (a) is done by rotating the dewar around the vertical axis, and the vertical one (b) by tilting the dewar. The measurements are done for two orthogonal polarizations of the signal. When the polarization is vertical, the electrical field coincides with the direction of the long axis of the ellipse.

a)



b)

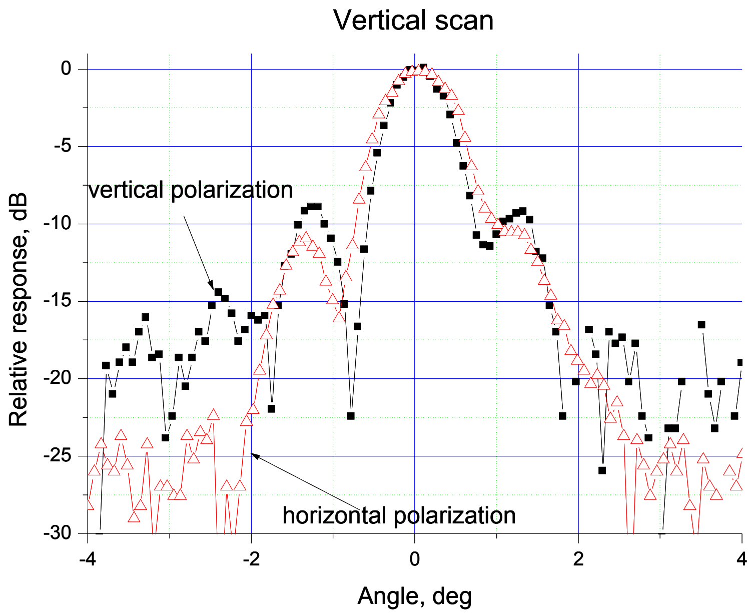


Figure 6. The measured beam pattern of the integrated antenna at 2.5 THz. The horizontal scan (a) is done by rotating the dewar around the vertical axis, and the vertical one (b) by tilting the dewar. The measurements are done for two orthogonal polarizations of the signal. When the polarization is vertical, the electrical field coincides with the direction of the long axis of the ellipse.

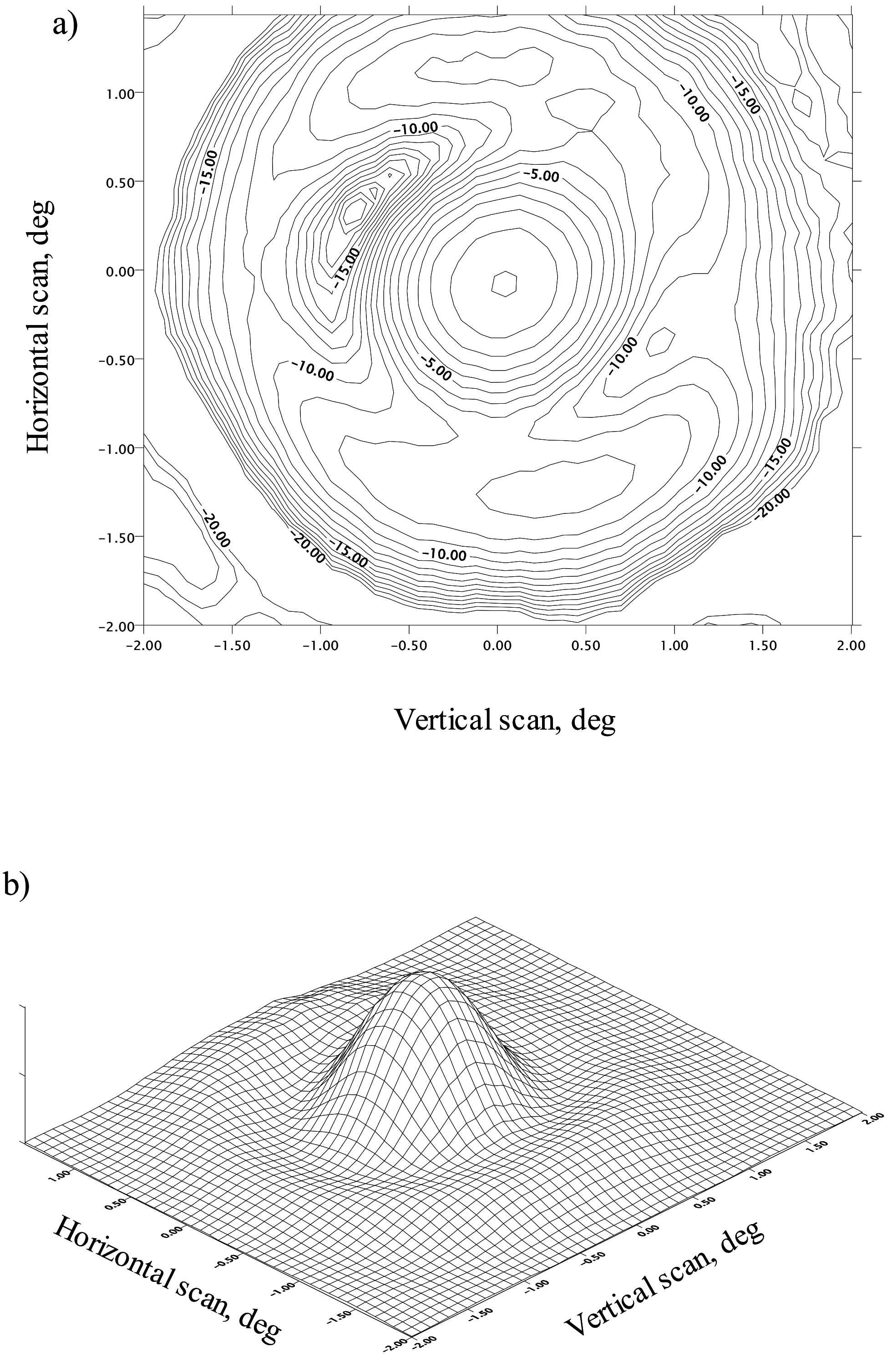


Figure 7. a) 2-D scan of the spiral antenna SEL combination at 2.5 THz. The relative response is in dB; b) 3-D view of the scan.