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Hologram-Based Compact Range for Submillimeter-Wave Antenna Testing

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***Abstract*—A hologram-based compact antenna test range (CATR) is being developed to overcome challenges met in antenna testing at submillimeter wavelengths. For the first time, this type of CATR has been built for testing of a large reflector antenna at submillimeter wavelengths. The CATR is based on a 3-m computer-generated hologram as the focusing element. This paper discusses the design and the construction of the CATR, and the verification of the CATR operation with quiet-zone tests done for the CATR prior to the antenna testing. Assembly of the CATR, testing of the 1.5-m reflector antenna at 322 GHz, and the disassembly were all done within two months in 2003. The quiet-zone field measurement results are analyzed in this paper. The CATR was concluded to be qualified for antenna testing. The antenna testing is described in a separate paper.**

***Index Terms*—Antenna measurements, compact antenna test range (CATR), computer-generated hologram, submillimeter wave.**

I. INTRODUCTION

THE goal of several ongoing space research projects is to study the Universe at submillimeter wavelengths. Satellite missions for such a task will carry electrically large reflector antennas, which should be tested prior to launch to ensure their proper function. The development of accurate submillimeter antenna test methods and facilities is needed for these tests. At millimeter wavelengths, the most widely used methods to measure the radiation pattern of a satellite antenna are the reflector-based compact antenna test range (CATR) and near-field scanning [1].

In a CATR, a spherical wave is transformed to a plane wave with a collimating element. The plane wave is used to measure the radiation pattern of the antenna-under-test (AUT). Since the dimensions of the range are relatively small, the CATR can be situated indoors and most of the problems caused by the atmosphere can be avoided. The AUT is placed into the quiet-zone. Typical criteria for the field in the quiet-zone are that the amplitude and phase deviations of the plane wave do not exceed 1 dB and 10°, peak-to-peak, respectively. In a conventional CATR, the focusing element is a reflector or a set of two [2] or three reflectors. The main reflector has to be clearly larger than the AUT. In the submillimeter-wave range, a very high surface accuracy is required ($\sim 0.01\lambda$ that is, e.g., 10 μm at 300 GHz) [3], which makes manufacturing of large reflectors difficult and highly expensive.

In a CATR, measurements can be done in a reasonably short period of time and a real time field value is available. This is a significant advantage compared to the near-field scanning where large amounts of near-field data first have to be acquired [4] and then transformed to get the field value. The time needed for a near-field measurement is very long (even several days), and thus the measurement system has to be very stable.

The Radio Laboratory of the Helsinki University of Technology (TKK) is developing a novel type of CATR, which is suitable for submillimeter wavelengths. The CATR is based on a computer-generated amplitude-type hologram as the focusing element [5]. Computer-generated holograms (diffractive elements) [6] can be used for shaping submillimeter-wave beams. A hologram in general is a record of an interference pattern of two wave fronts. Computer-generated submillimeter-wave holograms can be also regarded as locally periodic diffraction gratings that modify both the reflected and transmitted fields. In practice, the interference pattern is binarized to form a slot pattern, which consists of nearly vertical, slightly curved slots etched on a metal layer on top of a thin dielectric film. As the hologram is a transmission type element its surface accuracy requirement is much lower than that of a reflector and, therefore, at submillimeter wavelengths, it is easier to manufacture. A simple, planar structure makes the hologram relatively inexpensive to manufacture. Adequate surface flatness is ensured by tensioning the hologram to a frame. Due to a light weight and compact structure of the hologram, the hologram can be transported to the satellite test site where the CATR is then constructed. Therefore transporting of an antenna integrated on a heavy and sensitive satellite to the antenna test site is not necessary.

Previously, hologram-based CATRs have been used at frequencies of 39, 119, and 310 GHz [7]–[9]. In 1998, the Odin satellite telescope was tested successfully at 119 GHz with a hologram-based CATR [8]. Now, for the first time, a hologram-based CATR has been built for antenna testing at submillimeter-wave frequencies. In 2003, a temporary hologram-based CATR

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was constructed in a large research hall. The assembly of the range, the antenna measurements and the disassembly of the range were done in about two months. The range was used for testing of a large reflector antenna, the ADMIRALS RTO (representative test object) at 322 GHz. The ADMIRALS RTO has been constructed by EADS Astrium, Germany, and it is used for demonstrating the current satellite antenna technology and for comparing the potential antenna testing methods in activities organized by ESA/ESTEC. The diameter of the parabolic main reflector of the RTO is 1.5 m and the total weight is about 400 kg. The offset-feed is placed 3 m away from the main reflector. The antenna testing is presented in a separate paper [10].

II. THE 3-m HOLOGRAM AT 322 GHZ

A. Design of the Hologram

A hologram for generating a high-quality plane-wave can be designed with electromagnetic simulation [5], [11]. The hologram structure is analyzed with the finite-difference time-domain (FDTD) method. This gives the field in the aperture of the hologram, from which the field in the quiet-zone is calculated with PO (physical optics). On the basis of simulation results, the computer-generated hologram pattern is optimized for the best performance.

The transmission of the slots in the hologram pattern depends on the polarization of the incident field. Currently, holograms operate at the vertical polarization, i.e., the electric field of the feed antenna is vertically polarized.

A hologram operating at 322 GHz was needed for measuring a 1.5-m reflector antenna. It was estimated that to measure the antenna with sufficient accuracy, the diameter of the quiet-zone had to be at least 1.8 m, i.e., the antenna had to fit well inside the quiet-zone. According to the simulations, a hologram of 3 m in diameter produced a quiet-zone of this size when it was fed by a corrugated horn antenna.

The schematic layout of the CATR operating at 322 GHz is shown in Fig. 1. The hologram is designed so that the plane-wave propagates at an angle of 33° relative to the normal to the hologram. Also other beams [12] diffract from the hologram, but they are terminated by absorbers (e.g., Eccosorb VFX-NRL-2). The orientation of the feed antenna relative to the hologram affects the generated hologram pattern. To make the hologram pattern less sensitive to possible systematic manufacturing errors, the slots are designed to be as wide as possible and equal in width in the midsection of the pattern. Here, an optimal result is achieved when the feed is placed at a distance of 9 m and moved by 0.8 m in the transversal direction from the optical axis of the hologram. Displacement in the transversal direction affects the spacing and the widths of the slots in the generated hologram pattern. This makes the slots more equal in width. For optimal illumination, the feed is also rotated by 3.7° toward the center point of the hologram. The edge illumination is then $-5.0\ \mathrm{dB}$ and $-2.8\ \mathrm{dB}$, on the left edge and on the right edge of the hologram, respectively. To avoid edge diffraction, the slots are tapered down to 30 $\mu\mathrm{m}$ in width at the edges of the hologram. The slots in the mid-section of the pattern are 270–325 $\mu\mathrm{m}$ wide. The metal strips are 900–1920 $\mu\mathrm{m}$ wide.

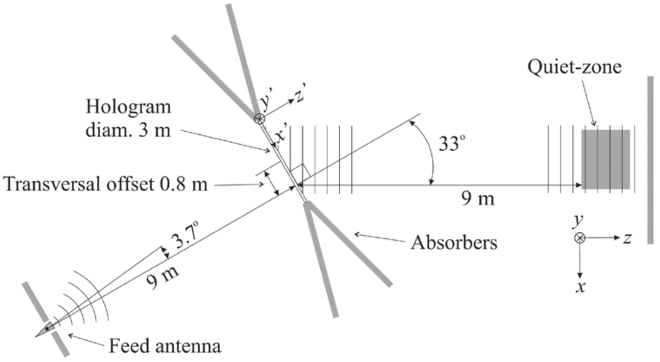


Fig. 1. Schematic layout of the hologram-based CATR operating at 322 GHz.

An appropriate material is needed for the hologram. Previous experience has shown that a copper-laminated Mylar film is a suitable material for holograms. It is mechanically durable and easy to process. Also, its electrical characteristics are good: it has a low loss and a low relative permittivity (3.3 for Mylar). A 50 $\mu\mathrm{m}$ Mylar film with a 17 $\mu\mathrm{m}$ copper-laminate was chosen as the material and the hologram was optimized for this film.

The quiet-zone was optimized at a distance of 9 m from the hologram. According to the simulations, the quality is good also at other distances from the hologram. The simulated amplitude and phase ripples are less than 0.5 dB and 5°, peak-to-peak. The width of the quiet-zone is 1.95 m that is 65% of the diameter of the hologram.

B. Manufacturing of the Hologram Pattern

Several manufacturing methods were investigated for the manufacturing of the hologram pattern [13]. According to the simulations, the manufacturing accuracy of the pattern should be about 0.01–0.02 λ, i.e., 9–19 $\mu\mathrm{m}$ at 322 GHz. Sufficient accuracy could be achieved in many ways. For example, the conventional printed circuit board (PCB) technique could be accurate enough at 322 GHz. The PCB technique is based on chemical wet-etching with photo masks.

It was found that processing the hologram pattern in a single piece is not currently possible at any commercial manufacturing facility available. Therefore, the hologram had to be constructed from several separately manufactured pieces, which were joined together. Large pieces with a high accuracy can be processed by using direct laser exposure of the pattern with chemical wet-etching. The manufacturing accuracy increases since photo masks are not needed. In the commercial facility we used, the maximum area that can be processed in a single piece is 1.35 m × 3.2 m. Fig. 2 shows how the 3-m hologram was constructed from three 1 m × 3 m (height × width) pieces.

The hologram pattern was generated with the accuracy of 5 $\mu\mathrm{m}$. Several experimental tests were done to optimize the manufacturing process. The realized manufacturing accuracy was examined with a microscope. Fig. 3 shows the measured slot widths along the two seams on the edge of each piece. Also, the designed slot widths are shown. Slot widths were measured at the interval of 0.15 m and the measurement uncertainty was estimated to be $\pm 15\ \mu\mathrm{m}$. As can be seen in Fig. 3, the slots are etched with sufficient accuracy. The average manufacturing

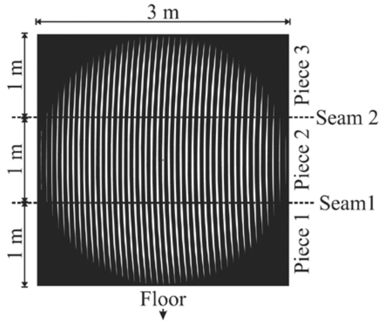


Fig. 2. The 3-m hologram at 322 GHz constructed from three pieces.

error is 10 $\mu\mathrm{m}$ and no significant systematic error is seen. The etching quality of the narrow slots on the edges is also good.

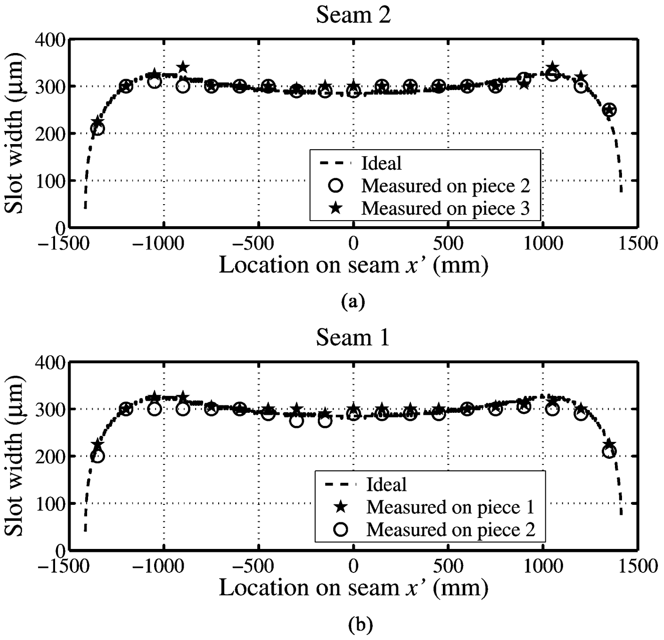
C. Joining of the Hologram Pieces

Different techniques (glueing, taping and soldering) were studied for joining of the hologram pieces. After numerous experiments, soldering was found to be the best method to join the pieces together [13]. A soldered seam is electrically almost invisible when the pieces are aligned accurately. The result is much better than with glueing or taping, which can cause significant disturbances to the quiet-zone field [13]. In soldering, metal strips are joined together in the vertical direction. A horizontal seam is better compared to a vertical seam since the precise alignment of pieces is easier and the seam is also more durable. The mechanical strength of the soldered seam has also been tested and the seam was found to be durable.

III. SCALE MODEL TESTS

Alignment and soldering of hologram pieces was studied by constructing a 1:5 scale model of the 3-m hologram. The 0.6-m model operated at 322 GHz and it was constructed from three pieces, each of them was 0.2 m × 0.6 m in size. The pieces were manufactured on the 50 $\mu\mathrm{m}$ Mylar film using the conventional PCB technique with masks. The manufacturing quality of the pieces was adequate for this purpose. The aim of this work was to develop a suitable technique and equipment to align and to solder the hologram pieces together. A similar technique and equipment were later used for the assembly of the 3-m hologram.

The scale model was constructed on a 0.6 m × 0.6 m vacuum table. The table consists of a metal plate with holes and of a vacuum pump providing suction through the metal plate. The hologram pieces are placed on the table and the vacuum holds them in place during the whole joining process. The use of the vacuum table allows accurate alignment of the hologram pieces. The seams were illuminated from below by LEDs, which were embedded in the table and covered by plexiglass. The pattern in each piece extended over the seam by 5 mm. The pieces could be aligned accurately when they overlapped each other on the edge. Alignment was done with a microscope by observing the alignment of transparent slots and small 3-mm cross marks located on the edge of each piece. After alignment, the pieces were cut with a surgical scalpel, which was moved on a linear rail placed over the seam. Perfect matching of the edges was ensured by cutting the pieces one on top of the other. After soldering the hologram was tensioned into a frame. Fig. 4 shows the scale model in the frame. Both horizontal seams are indicated in the figure.



(a)

(b)

Fig. 3. Ideal and measured slot widths along the two seams of the 3-m hologram.

The quiet-zone was tested at 322 GHz using a planar scanner and the AB Millimètre MVNA-8-350 vector network analyzer. A corrugated feed horn was placed at a distance of 1.8 m and the quiet-zone was probed at 1.8 m from the hologram. The planarity of the scanner was measured with a laser-tracker, and the planarity data were used to correct the measured phase values. The phase error caused by the flexing LO cable of the receiver was also removed [14]. To verify the design, the geometry and dimensions of the measurement setup were the same as in the large CATR except in 1:5 scale.

Fig. 5 shows the xy-scan of the quiet-zone field of the scale model hologram. Also, the vertical cut at $x = 0$ is shown.

According to the simulation, the simulated quiet-zone diameter inside the -1 dB amplitude taper is 0.38 m. In this region, the measured amplitude and phase ripples are 1.5 dB and 10°, peak-to-peak. The quality of the field is good over the whole quiet-zone beam. The estimated alignment accuracy of the pieces is better than 30 $\mu\mathrm{m}$ in the direction parallel to the seams and 50 $\mu\mathrm{m}$ in the direction perpendicular to the seams. The small misalignment of the pieces is seen in the vertical cut as some ripple in the amplitude (ca. 1 dB, peak-to-peak) and changes in the phase (ca. 10°, peak-to-peak). The locations of the seams are at $y = -100$ mm and $y = 100$ mm. The good results indicate that the methods developed in the scale model tests can be also used for the 3-m hologram.

IV. CONSTRUCTION OF THE CATR

A. The 3-m Hologram

The 3-m hologram was constructed on a 3 m × 3 m vacuum table. After cutting the pieces, alignment was rechecked with a microscope. The alignment accuracy of the pieces at the seams was better than 10 $\mu\mathrm{m}$ in the midsection of the seams. However,

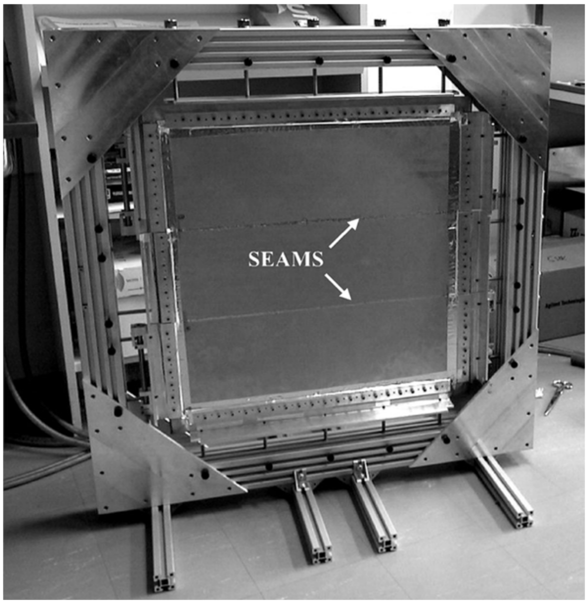


Fig. 4. The 1:5 scale model hologram in the frame. Three pieces are soldered together; two horizontal seams can be seen.

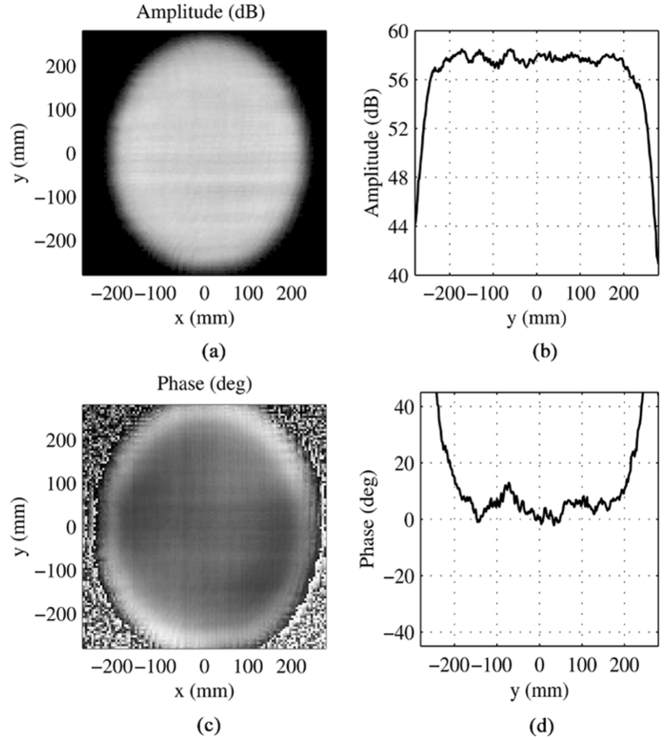


Fig. 5. Measured quiet-zone field amplitude and phase of the 1:5 scale model hologram at 322 GHz. The seams are at $y = -100$ mm and $y = 100$ mm.

at the ends of the other seam the maximum alignment error was up to 0.6 mm and 1.0 mm in the direction perpendicular to the seam.

Altogether 3840 metal strips were soldered in the two seams. The quality of soldering was inspected with a microscope and it was found to be very good. Fig. 6 shows how the 3-m hologram was soldered with an ordinary soldering iron and tin solder. The inset shows soldered metal strips.

Fig. 6. Soldering of the 3-m- hologram. Soldered metal strips are shown in the inset.

After the pieces were soldered together, the hologram was attached to a frame made of 80 mm aluminum profile and tensioned carefully. The hologram was erected with a pulley and rope and the vacuum table was removed. The final tensioning of the hologram was done in the upright position.

B. Range Setup

The CATR was built in a large research hall of the Helsinki University of Technology. The hall with dimensions of 16 m × 19 m × 31 m (height × width × length) is not intended for antenna measurements as there are some fixed metal structures in the hall. Therefore the layout and geometry of the CATR had to be designed carefully. Fig. 7 shows the layout of the CATR and Fig. 8 a photograph of it. Absorber walls were used around the hologram to block the spillover radiation of the feed. In the vicinity of the feed, the hologram, and the AUT, high-quality absorbing material (Eccosorb VFX-NRL-2) was used to eliminate standing waves and reflections. This absorbing material is designed for millimeter-wave frequencies and it has a pyramidal nonpainted surface. It was also used to terminate the beam propagating directly through the hologram.

Convoluted millimeter-wave absorbers, carbon-tipped microwave absorbers, and floor carpets were used in less critical areas. Reflectivity of absorber materials and floor carpets has been studied in [17].

C. Submillimeter-Wave Instrumentation

The quiet-zone amplitude and phase were measured using a linear scanner and the AB Millimètre MVNA-8-350 vector network analyzer. A transmitter delivered with the ADMIRALS RTO was used in the quiet-zone testing due to its high transmit power (2.6–5.4 dBm) [16]. A computer-controlled xyz-positioner was used for tuning the feed position to optimize the quiet-zone field. The feed (a corrugated horn) could also be turned in the azimuth and elevation planes to achieve a proper hologram illumination. The quiet-zone was probed with a corrugated feed horn. A lightweight receiver consisting of a Schottky harmonic mixer pumped with a phase-locked Gunn oscillator was used with the linear scanner. Phase errors caused

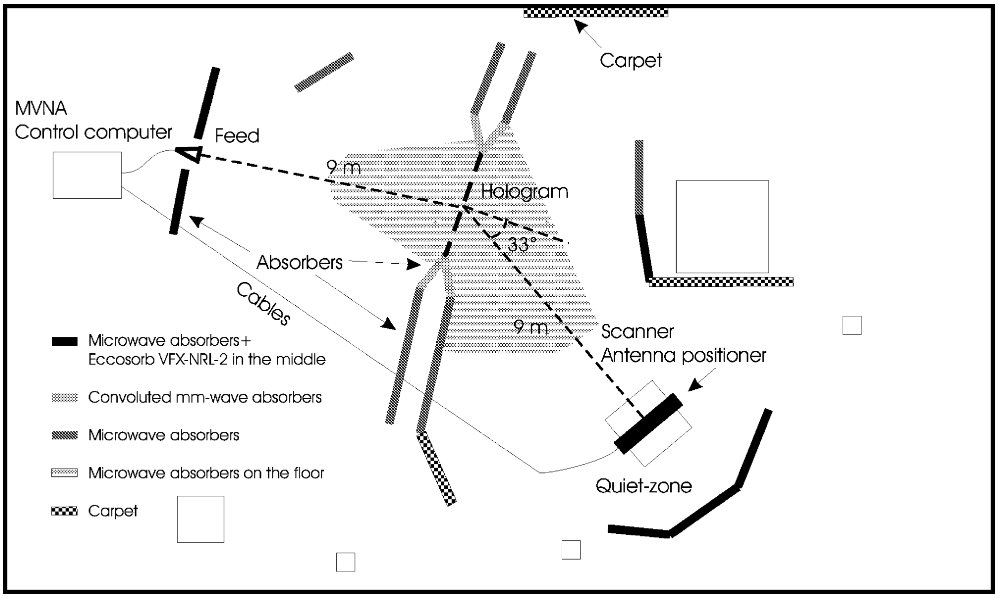


Fig. 7. Layout of the CATR.

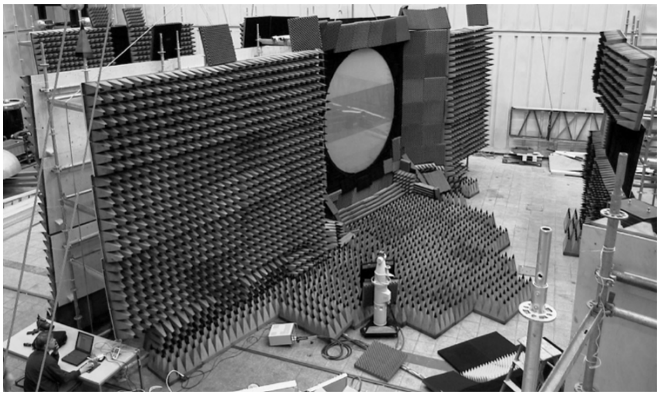


Fig. 8. Overview of the compact range.

Fig. 9. Plane-Polar quiet-zone scanner mounted on the antenna positioner during instrumentation tests.

by the flexing LO cable of the receiver were corrected by using a system developed at the Radio Laboratory [14].

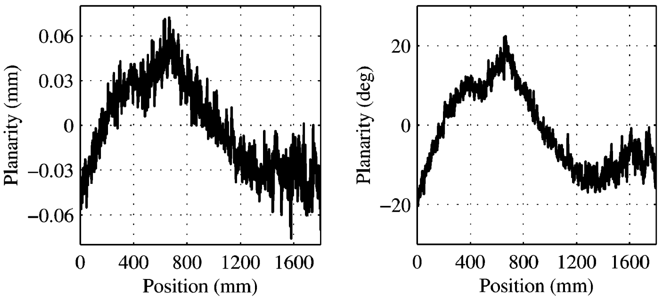
D. Antenna Positioner

An antenna positioner was needed to rotate the AUT. The TKK Laboratory of Machine Design constructed it from a Bofors anti-aircraft gun (see Fig. 9). Only the base and the azimuth gear were conserved. The cradle-type elevation positioner was made from rigid steel profile. New AC drive—controlled motors with gearboxes were installed on both axes. Twenty-six bit absolute angle encoders (Heidenhain RCN-226) were placed directly on the axes of rotation. They are capable of measuring 0.0001° steps requiring no origin calibration. Repeatability of movement with the original azimuth gear was measured to be 0.0004°. The angular ranges for the antenna tests were 360° in azimuth, and $-12^\circ \cdots +90^\circ$ in elevation.

E. Linear Scanner

The TKK Laboratory of Machine Design constructed also a plane-polar scanner structure that was mounted on the antenna positioner during the quiet-zone testing (see Fig. 9). The 2-m-long scanner wing can be rotated around its center point to horizontal, vertical, and diagonal positions. The axis of rotation of the scanner was in the same point as the center point of the antenna under test. The antenna positioner and the linear scanner were controlled by a LabVIEW-based software.

During the first quiet-zone scans, the planarity of the scanner was measured in the horizontal, vertical, and diagonal positions with a three–dimensional (3-D) Leica laser tracker. The measured quiet-zone phase data was corrected with the acquired laser-tracker data. The shape of the linear scanner wing slightly altered between different positions. This is due to the heavy motor placed at the end of the scanner that bent the wing with a different force in different positions. Therefore, the position



(a) (b)

Fig. 10. Laser-Tracker measurement. A planarity measurement in the horizontal position (on the left side), and the average of four planarity measurements converted to degrees of phase at 322 GHz (on the right side).

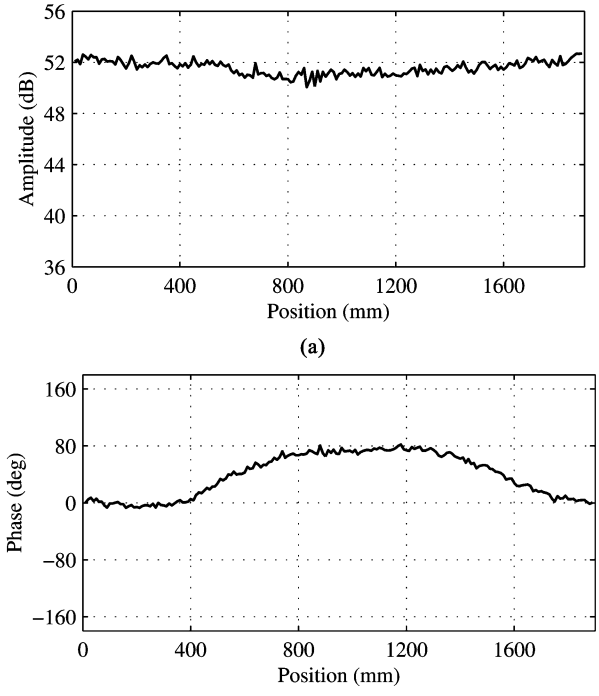
of the scanner had to be taken into account in the phase correction. The planarity was measured several times at different positions and the average of the measurements in each position was used for correcting the quiet-zone phase. A planarity measurement in the horizontal position and the average of four measurements at 322 GHz are shown in Fig. 10. After averaging, the planarity error that was compensated is equivalent to 40° in phase, peak-to-peak, and the ripple is ±3°. In the vertical direction, the planarity error is ca. 20°, peak-to-peak.

V. QUIET-ZONE TESTING

The quiet-zone field was adjusted iteratively by tuning the position of the feed horn on the basis of the quiet-zone scans. The quiet-zone field was optimized in the horizontal and vertical directions. The direction of the plane wave could be steered by moving the feed horn in the transversal plane. The adjustment of the distance between the feed and the hologram was used for setting the feed to the focus of the hologram. The pointing direction of the feed horn was adjusted to optimize the amplitude of the quiet-zone field.

The quiet-zone was probed at vertical polarization. Figs. 11 and 12 show a horizontal and a vertical scan of the optimized quiet-zone field. In all phase results shown here, errors caused by the flexing LO cable and the nonplanarity of the scanner have been corrected. The S/N ratio in the quiet-zone testing was about 52 dB. At this dynamic range, the MVNA has an uncertainty of 0.03 dB and 0.3°. The center point of the aperture of the antenna under test is at 980 mm in the scanner coordinate system during the antenna measurements. In the region where the antenna under test (range 200–1750 mm) is, the maximum deviations are about 2.6 dB and 250°, peak-to-peak. The maxima occur in the boundary zone. The short-period amplitude and phase ripples are 1 dB and 10°, peak-to-peak.

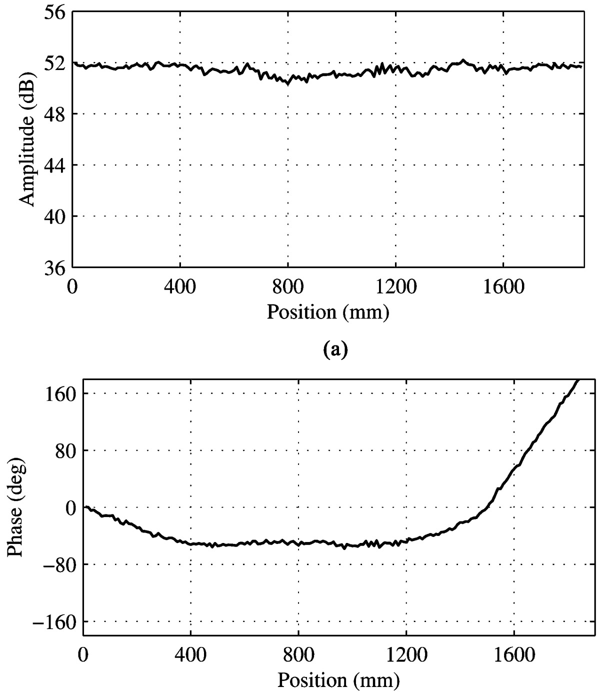
Two features can be clearly seen in the results. The amplitude has a 1–1.2 dB dip in the middle of the quiet-zone and the phase front is convex in the horizontal direction while it is concave in the vertical direction. The phase deviations are ca. 45°, peak-to-peak, in the diagonal directions. Thus, the equiphase surface of the quiet-zone is saddle-shaped. A more detailed analysis of the effect of the quiet-zone quality to the antenna measurement accuracy is presented in [10].



(a)

(b)

Fig. 11. Horizontal scan of the quiet-zone field.



(a)

(b)

Fig. 12. Vertical scan of the quiet-zone field.

VI. ANALYSIS OF THE QUIET-ZONE TEST RESULTS

The amplitude dip of 1–1.2 dB in the middle of quiet-zone is potentially due to a slightly inaccurate modeling of the hologram structure in the FDTD simulation. This kind of dip was not seen in the scale model measurements. The amplitude dip appears also in the simulation results when the slots are modeled more accurately using a smaller FDTD cell size. Therefore, the

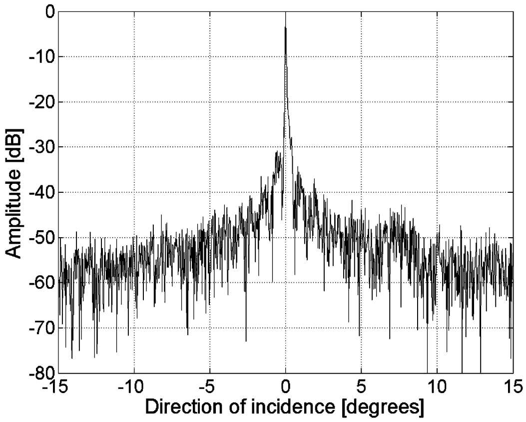


Fig. 13. Normalized angular spectrum of the quiet-zone field in the azimuth plane.

amplitude dip can be avoided in the future by using more accurate FDTD modeling.

After the antenna tests, the dimensions of the hologram were measured when the hologram was still in upright position and tensioned. According to measurements, the hologram was 3 m in width (the estimated measurement accuracy was ±1 mm). However, the height of the hologram was not 3 m but ca. 10 mm less. Since this deformation cannot be seen in the hologram pattern files (including the overlapping alignment markers in the hologram pieces) sent to the manufacturer, most likely an error had occurred in the pattern etching process. Simulations done for this deformed hologram pattern suggest that the observed 250° phase deviation in the quiet-zone field is mainly caused by the deformed pattern. The perpendicular alignment error was considerable especially at the ends of the upper seam (0.6-1.0 mm). Therefore, a part of the phase distortions are apparently caused by the alignment of the pieces. Alignment inaccuracy may also result from the deformation of the hologram pieces.

Reflections from the environment may cause short-period amplitude and phase distortions. The measurement result might be too optimistic if the quiet-zone field is sampled coarsely and a high directivity antenna is used as the probe. Here, the quiet-zone scans were made with a step of 10 mm and a corrugated horn antenna was used as a probe. For an analysis of the quiet-zone field, a scan with a step of 0.45 mm was made. The step was less than half wavelength in free space at 322 GHz. The probe antenna was changed to an open-ended waveguide, which had smaller directivity than the corrugated horn antenna. No significant difference was seen in the measured amplitude and phase ripples compared to the previous result. This suggested that there were no clear reflections in the hall, and that the quiet-zone measurement results are reliable. The angular spectrum of the quiet-zone field was also used to identify reflections. Fig. 13 shows the normalized angular spectrum computed in the azimuth plane. The peak at the direction of 0° is the plane wave propagating in an angle of 33°. A small disturbance can be recognized at the direction of $+8^\circ$, and it causes a distortion to the measured antenna radiation pattern.

VII. SUMMARY AND CONCLUSION

We have constructed and tested a large hologram-based CATR at 322 GHz. This was the first time when a hologram-based CATR was constructed for dedicated submillimeter- wave antenna tests. The antenna test results will be presented in a separate paper [10]. A measurement system consisting of RF instrumentation, antenna positioner, and linear scanner for quiet-zone testing was constructed. A suitable material and manufacturing facility was found for the hologram. As the maximum area that can be processed is 1.35 m × 3.2 m, the hologram pattern was manufactured in three pieces, which were joined together. A special setup was constructed to align and join the pieces. Soldering was used successfully for joining the hologram pieces.

The quiet-zone field was tested successfully. The antenna test range was found to be suitable for antenna testing at 322 GHz. The quiet-zone of the 322-GHz CATR had a 1–1.2 dB amplitude dip and a saddle-shaped equiphase surface (peak-to-peak deviation 250°). A slight inaccuracy in the FDTD modeling of the hologram, the manufacturing, and alignment of the pieces were identified as the main reasons for the amplitude and phase deviations in the quiet-zone field. In the future, the FDTD modeling of the hologram and the hologram manufacturing can be corrected. The alignment of the pieces should be studied more if large (i.e., larger than 1.35 m × 3.2 m) holograms for even higher frequencies need to be constructed from several pieces.

The CATR was a temporary setup. Only two months were needed for assembling the range, for measuring an antenna, and for disassembling the range. The hologram has a lightweight, planar structure, which enables transporting the hologram to the satellite test site and building up the CATR there. Therefore, transporting expensive satellites can be avoided. The hologram has a low manufacturing cost, which makes a custom-built CATR possible.

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