Experimental Study on a Hologram-Based Compact Antenna Test Range at 650 GHz

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***Abstract*—This paper studies the feasibility of a hologram-based compact antenna test range (CATR) for submillimeter-wave frequencies. In the CATR, a hologram is used as a collimating element to form a plane wave for antenna testing. The hologram is a computer-generated interference pattern etched on a thin metal-plated dielectric film. Two demonstration holograms of approximately 1 m in diameter were designed for 650 GHz, and they were manufactured on two different Mylar films. The holograms were illuminated with a horn, and the plane-wave field was probed at 644 GHz. The measured amplitude and phase ripples were 2 dB and 15° peak-to-peak for one of the holograms. A higher quiet-zone field quality can be achieved by increasing the manufacturing accuracy by further manufacturing tests. After this, the hologram-based CATR should have a potential for high-quality antenna tests at frequencies up to 650 GHz.**

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

I. Introduction

OBSERVING THE earth or the universe in the submillimeter-wave range (300–3000 GHz) gives additional information that is not available in the visible range. For example, chemical compounds that cause ozone depletion have strong absorption lines at submillimeter wavelengths, e.g., around 640 GHz. In addition, a large part of luminosity of the universe and a significant amount of photons originating from the post-big-bang universe lie in the submillimeter-wave region. These phenomena can be studied with earth orbiting satellites, which utilize very large reflector antennas [1], [2].

Manufacturing of a large submillimeter-wave reflector antenna and its feed system is an extremely demanding task. Proper radiation characteristics of the antenna should be verified by antenna radiation pattern measurements to avoid possible errors in construction. The compact antenna test range (CATR) is a suitable method for this purpose [3]. In the CATR, the plane wave needed for antenna testing is created by a collimating element, which is conventionally a set of 2–3 reflectors. The antenna under test (AUT) is placed in the quiet zone, which is a region where the plane wave has a high quality. A reflector-based CATR has been used for antenna testing at frequencies up to 500 GHz [4]. The CATR main reflector has to be clearly larger than the AUT, and its surface accuracy has to be much higher than one of the AUT. The rms surface accuracy requirement of the CATR reflectors is approximately $\lambda/100$ [5] or 4.6 μm at 650 GHz, which is very difficult and expensive to accomplish.

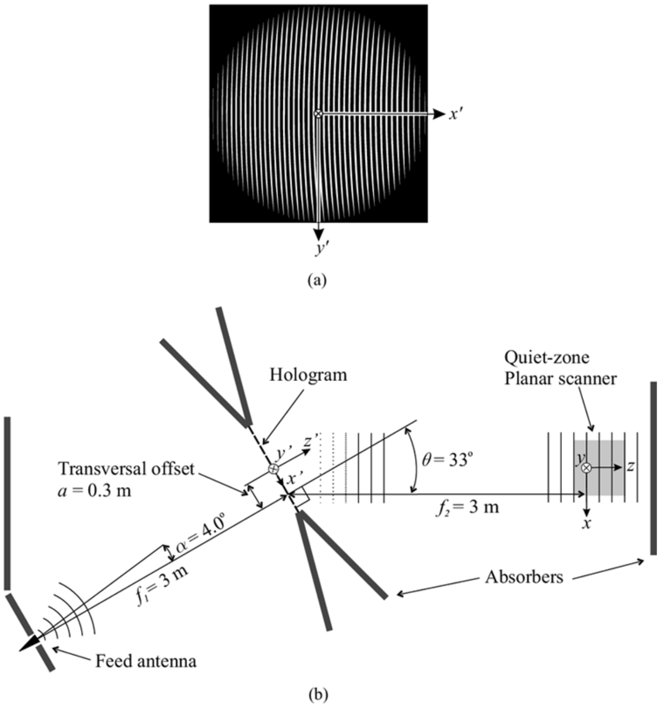

Fig. 1. (a) Example of a hologram pattern. (b) Schematic view of the demonstrative hologram-based CATR at 650 GHz.

A transmission-type binary amplitude hologram is an alternative to reflectors [6]. The planar hologram used in CATR is a computer-generated interference pattern etched on a thin metal-plated dielectric film. See Fig. 1(a) for an example of the amplitude hologram pattern. In this figure, nearly vertical slightly curved microwave transparent slots are in white and metal strips between them in black. The hologram is tensioned to a rigid frame that ensures its flatness. The rms planarity

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requirement of the hologram is approximately $\lambda/10$ [7]. According to simulations, in the direction parallel to the hologram plane, the required accuracy of the pattern is approximately $\lambda/100 - \lambda/50$. The planar structure and much lower surface accuracy requirement make manufacturing of a hologram simpler and less expensive than that of a reflector. Facilitated manufacturing is a significant advantage, especially at frequencies above 1000 GHz, where future scientific space research missions will operate.

In 2003, a hologram-based CATR was used for measuring the radiation pattern of a 1.5-m parabolic reflector antenna at 322 GHz [8]. Now, for the first time, a demonstrative hologram-based CATR was constructed for 650 GHz. In this paper, the design and manufacturing of two demonstrative holograms are first described. Secondly, a measurement setup for testing of the holograms is presented, and the test results are shown. Finally, the applicability of the hologram-based CATR for high submillimeter-wave frequencies is considered on the basis of the results obtained in this study.

II. DESIGN OF TWO DEMONSTRATIVE HOLOGRAMS

A. Design

Two amplitude holograms of approximately 1 m in diameter were designed for 650 GHz. The holograms were manufactured on different substrates. The diameter was limited to 1 m to keep the dimensions of the test range relatively small so that it could be built up in a small laboratory room. The computer-generated hologram patterns were optimized by using a finite-difference time-domain (FDTD)-based simulation method, which was developed earlier by MilliLab, Helsinki University of Technology, Espoo, Finland [6], [9]. The holograms in this paper are designed to operate at the vertical polarization, i.e., the electric field of the feed antenna is vertically polarized. The FDTD simulations have been done at this polarization.

The geometry of the test range is presented in Fig. 1(b). The same geometry was used for both holograms. A corrugated horn antenna designed for 650 GHz and having a Gaussian beam was used as the feed. The feed was placed at a distance of 3 m from the hologram. It was moved 0.3 m from the axis of the hologram and rotated 4.0° toward the center point of the hologram. Moving of the feed in the transversal direction affects the spacing of slots in the generated hologram pattern and makes the slots more uniform in width in the midsection of the pattern, which facilitates manufacturing. Furthermore, in this geometry, the amplitude taper and edge illumination are reasonable in the hologram area, which simplifies optimization of the pattern. The hologram pattern is designed so that the generated plane wave propagates in an angle of 33° in respect to the norm of the hologram [6], [10]. The quiet-zone field is optimized at a distance of 3 m from the hologram.

B. Substrate Materials

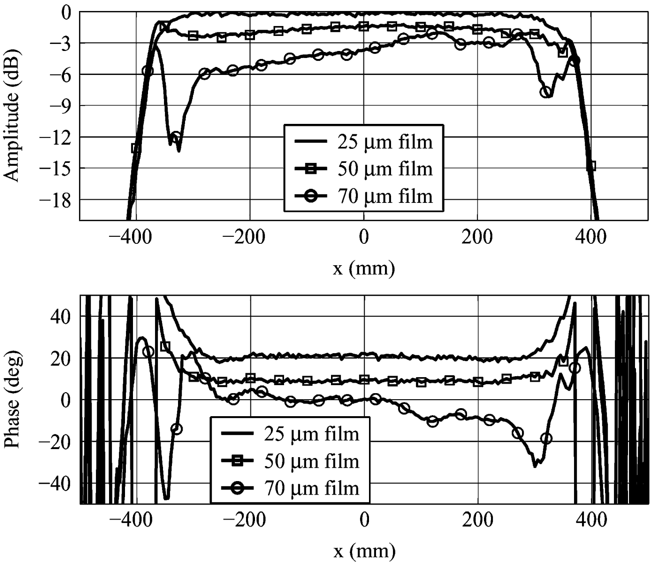

Fig. 2. Simulated horizontal cut of the quiet-zone field of a 1-m hologram at 650 GHz for three thicknesses of the substrate: 25, 50, and 70 μm. The curves are shifted for clarity.

Appropriate substrate materials were needed for the holograms. Previous experiments at lower frequencies have shown a copper-laminated Mylar film (with a relative permittivity of 3.3 for Mylar) to be an electrically good (low losses, high homogeneity) and mechanically durable substrate for holograms. Therefore, copper-laminated Mylar was chosen as the substrate material. According to the simulations, the thickness of the Mylar film should not be greater than 50 μm at 650 GHz. Otherwise, the field within the film resonates, which disturbs the field in the quiet zone. This can be seen in the simulation results presented in Fig. 2. This figure shows a simulated horizontal cut of the quiet-zone field of a 1-m hologram at 650 GHz at a distance of 3 m from the hologram. The hologram is designed for the 25-μm film, and the simulation is done for three thicknesses of the substrate: 25, 50, and 70 μm. Slight disturbances in the quiet-zone field are recognizable when the 50-μm-thick film is used, and they are severe when the film is 70-μm thick. The resonances occur first on the edges of the hologram since the incident field propagates obliquely on the edges and, thus, the field travels a longer path inside the film.

As the focus of future satellite missions may well be at frequencies above 1000 GHz, a 25-μm Mylar film was chosen as the substrate material for one of the holograms (called Hologram I) to study processing properties of the film. This material should be applicable for holograms operating far above 1000 GHz. Too oblique incidence angle on the edges can be avoided by increasing the focal length/diamater (f/D) ratio of the hologram, i.e., by increasing the focal length (f) of the hologram or by reducing its diameter (D). The other hologram (called Hologram II) was designed for the 50-μm-thick Mylar film by reducing the diameter of the pattern by a few centimeters.

The copper-plating on top of the 25-μm film was 5-μm thick, and it was 17-μm thick on the 50-μm film. The skin depth of copper is only 0.082 μm at 650 GHz. Therefore, the copper plating in both films is sufficiently thick to prevent any leakage of radiation through it. Unwanted leakage could cause distortions to the quiet-zone field.

C. Design Results

A high quality of the quiet-zone field was verified by optimizing the hologram patterns for the substrate materials chosen.

TABLE I
DESIGN AND MANUFACTURING RESULTS FOR HOLOGRAM I (25-μm MYLAR +5-μm Cu) AND HOLOGRAM II (50-μm MYLAR +17-μm Cu)

	Hologram I Designed	Hologram I Manufactured	Hologram II Designed	Hologram II Manufactured
Diameter of the pattern	970 mm	970 mm	926 mm	866 mm
Slot widths in the mid-section	150–175 μm	180–230 μm ($\pm$7 μm)	135–170 μm	150–200 μm ($\pm$7 μm)
Slot widths on the left/right edge	$\geq$ 30 μm	90 μm/100 μm	$\geq$ 30 μm	105 μm/40 μm
Simulated peak-to-peak quiet-zone ripples	0.6 dB/5°	3.1 dB/6°	0.6 dB/5°	2.0 dB/6°
Simulated quiet-zone diameter	620 mm	620 mm	530 mm	520 mm

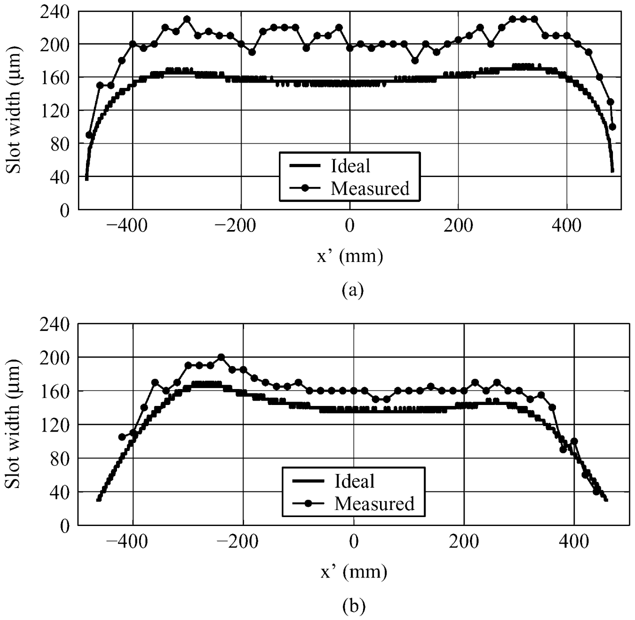

Fig. 3. Ideal and measured slot widths along the horizontal center line of the hologram $(y' = 0)$. (a) Hologram I. (b) Hologram II.

The properties of the holograms and simulation results are summarized in Table I together with manufacturing results. Hologram I has a diameter of 970 mm, and Hologram II has a diameter of 926 mm. Slot widths in the midsection of the pattern are 150–175 μm on Hologram I and they are slightly narrower on Hologram II. The slots are tapered down to 30 μm on the edges to prevent edge diffraction. The edge illumination is lower than -3.7 and -1.6 dB on the left/right-hand-side edge for both holograms. The diameter of the simulated quiet zone is approximately 620 mm for Hologram I and 530 mm for Hologram II. Amplitude and phase ripples are approximately 0.6 dB and 5° peak-to-peak for both holograms. The simulated quiet-zone fields are shown in Section III.

III. MANUFACTURING

The manufacturing method was based on direct laser writing of the hologram pattern on the photo resist on top of the substrate. After laser writing, chemical wet etching was applied to process the slots in the metal plating. According to the manufacturer, the nominal manufacturing accuracy of this method is 5 μm, which is sufficient at 650 GHz. The realized manufacturing accuracy was inspected with a camera microscope. Slot widths were measured along the horizontal center line of the hologram with an interval of 20 mm, and they are shown in Fig. 3(a) and (b). The estimated measurement accuracy was $\pm$7 μm.

The measured slot widths on Hologram I are systematically approximately 60 μm too large, i.e., the pattern is considerably overetched. The random deviation from the systematic error is at maximum $\pm$15 μm. Slots on Hologram II are overetched as well, but they are systematically only 20 μm wider than expected. The random error is here at maximum $\pm$5 μm. Tapered slots on the edges of Hologram I are 50 μm overetched. On Hologram II, the manufacturing error is smaller on the edges (at maximum 30 μm), but the tapered slots are not completely etched on the edges, i.e., the manufactured pattern is approximately 60 mm smaller than the designed one.

The effect of manufacturing inaccuracy was studied by simulations. Fig. 4 shows a horizontal cut of the simulated quiet-zone field at 650 GHz at 3 m from the hologram. Simulation was done for both holograms using the measured slot widths. The slot widths between the measurement points were linearly interpolated. Using the measured slot widths, the peak-to-peak ripples are 3.1 dB and 6° for Hologram I, and 2.0 dB and 6° for Hologram II. Simulation results for the ideal slot widths are shown for comparison.

A 1–2-dB amplitude taper can be seen in the quiet-zone fields. This is due to the overetching of the patterns. It is more severe for Hologram I because of the larger overetching. A 1.5–2-dB ripple on the edges of the quiet zones is caused by an improper edge tapering of the slots. According to simulations, the phase of the quiet-zone field is not affected significantly by the manufacturing inaccuracies. Only one hologram was manufactured on both films. Most likely, manufacturing error could have been reduced by manufacturing more holograms and tuning the manufacturing process to optimum. See Table I for a summary of the manufacturing results.

IV. MEASUREMENT SETUP

A. Submillimeter-Wave Instrumentation

The quiet-zone field was probed using a planar scanner. The amplitude and phase values of the field were measured with an AB Millimètre MVNA-8-350 vector network analyzer. Corrugated horn antennas (designed for 650 GHz) were used as the feed and probe antennas. An adequate dynamic range was achieved by using a powerful backward-wave oscillator (BWO) as the transmitter [11], [12] and a seventh-order Schottky diode harmonic mixer as the receiver.

It was noticed that the BWO gives 3 dB more power at 644 GHz than at 650 GHz. Therefore, the measurements were done at 644 GHz where a dynamic range of over 32 dB was achieved for both holograms. A small change in the operating frequency (here, the relative change was less than 1%) does not have a significant effect on the operation of the hologram. The

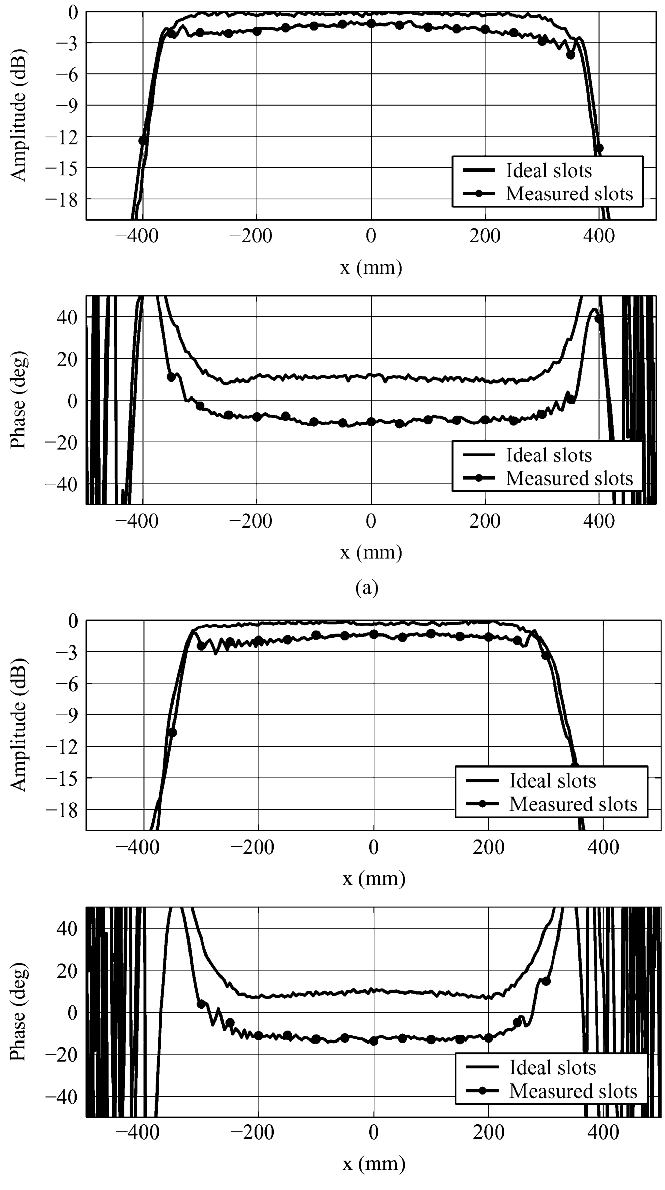

Fig. 4. Simulated quiet-zone field for ideal and measured slot widths at the horizontal cut $y = 0$ at 650 GHz. (a) Hologram I. (b) Hologram II. The curves for measured slot widths are shifted for clarity.

change in the operating frequency only steers the direction of the plane wave slightly (here from 33° to 33.35°).

B. Measurement Room and Planar Scanner

The quiet-zone tests were done in a small laboratory room with dimensions of $2.85\ \text{m} \times 6.35\ \text{m} \times 8.8\ \text{m}$ (height × width × depth). The hologram was in the middle of the room, and it was in an angle of 33.35° with respect to the planar scanner that was at a distance of 3 m. The transmitter was on the opposite side at 3 m from the hologram. All reflecting surfaces close to the feed and probe antennas, the frame, supporting structures, and the nonpatterned areas of the hologram were covered with absorbers. The spillover radiation was blocked by absorber walls around the hologram. The absorber material was nonpainted pyramidal Eccosorb VFX-NRL-2 that is designed for millimeter waves.

The receiver in the planar scanner is connected to the MVNA with a flexing RF cable. When the receiver is moved in the scanner, the RF cable bends, which changes its electrical length and causes an error to the measured phase value. The change in the electrical length can be measured with a pilot signal injected in the cable. A cable phase error correction system based on this method was used to correct phase errors caused by the flexing RF cable [13].

The planarity of the scanner was measured with a three-dimensional (3-D) laser tracker, and this planarity data was used for correcting the measured phase values. The uncertainty of the planarity measurement was approximately ±5–10 μm. The planarity measurement was done at normal room temperature, which might differ by a couple of centigrades from the temperature during the quiet-zone testing. For more accurate phase values, the movement of the probe should be measured with a laser tracker during the quiet-zone scanning.

V. QUIET-ZONE FIELD TESTING

A. Measurement Results

Fig. 5(a) and (b) shows the measured horizontal and vertical cut of the quiet-zone field at 644 GHz at 3 m from Hologram I. Fig. 5(c) and (d) shows the amplitude and phase in an xy scan. An amplitude ripple of approximately 4 dB peak-to-peak is seen in the horizontal cut, but not in the vertical cut where the peak-to-peak amplitude ripple is only 2 dB. In both cuts, approximately 2-dB amplitude tapering is recognizable. This is due to overetching of the pattern, as shown by simulations. Also, a 1.5-dB peak-to-peak amplitude ripple is seen on the edges of the quiet-zone field in the vertical cut. This is caused by the improper edge tapering of the slots. The phase ripple is approximately 15°–25° according to the horizontal and vertical cuts. In the whole quiet-zone area, the maximum ripples are approximately 4 dB and 50° peak-to-peak. The width of the quiet zone is approximately 700 mm in the horizontal direction and 870 mm in the vertical direction.

The measurement results for Hologram II are shown in Fig. 6(a)–(d). A 2-dB amplitude ripple is seen in the horizontal cut. In the vertical cut, the ripple is 1.5–2.0 dB. Amplitude tapering due to the overetching is not clearly seen. Also, no strong ripples on the edges of the quiet zone are recognized. The phase ripple is 10°–15° in the horizontal and vertical cuts. The maximum ripples are approximately 3 dB and 40° in the whole quiet-zone area. The width of the quiet-zone is approximately 600 mm in both directions. The measurement results are summarized in Table II.

It was noticed that the 25-μm film was slightly wrinkled prior to the etching process. When the hologram was tensioned to the frame and smoothed, the pattern was deformed. As the hologram structure changes more rapidly in the horizontal than in the vertical direction, the effect of pattern deformation is stronger in the horizontal direction. Also, uneven tensioning of the hologram in the frame can particularly cause phase distortions. These reasons can partly explain why the measured amplitude and phase ripples are larger than the simulated ones, and also why the distortions are larger in the horizontal than in the vertical direction.

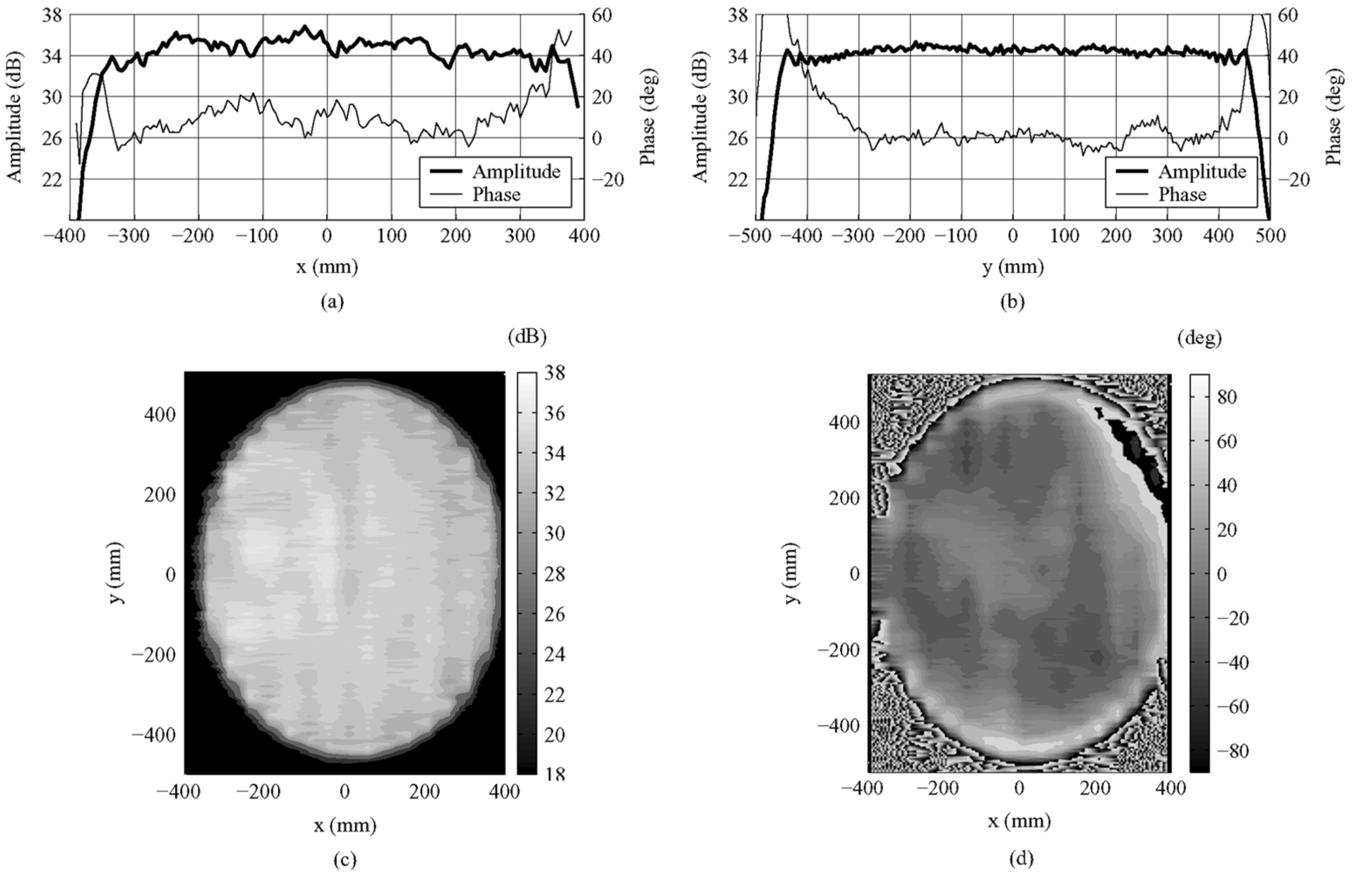

Fig. 5. Hologram I: measured quiet-zone field at 644 GHz at 3 m from the hologram.

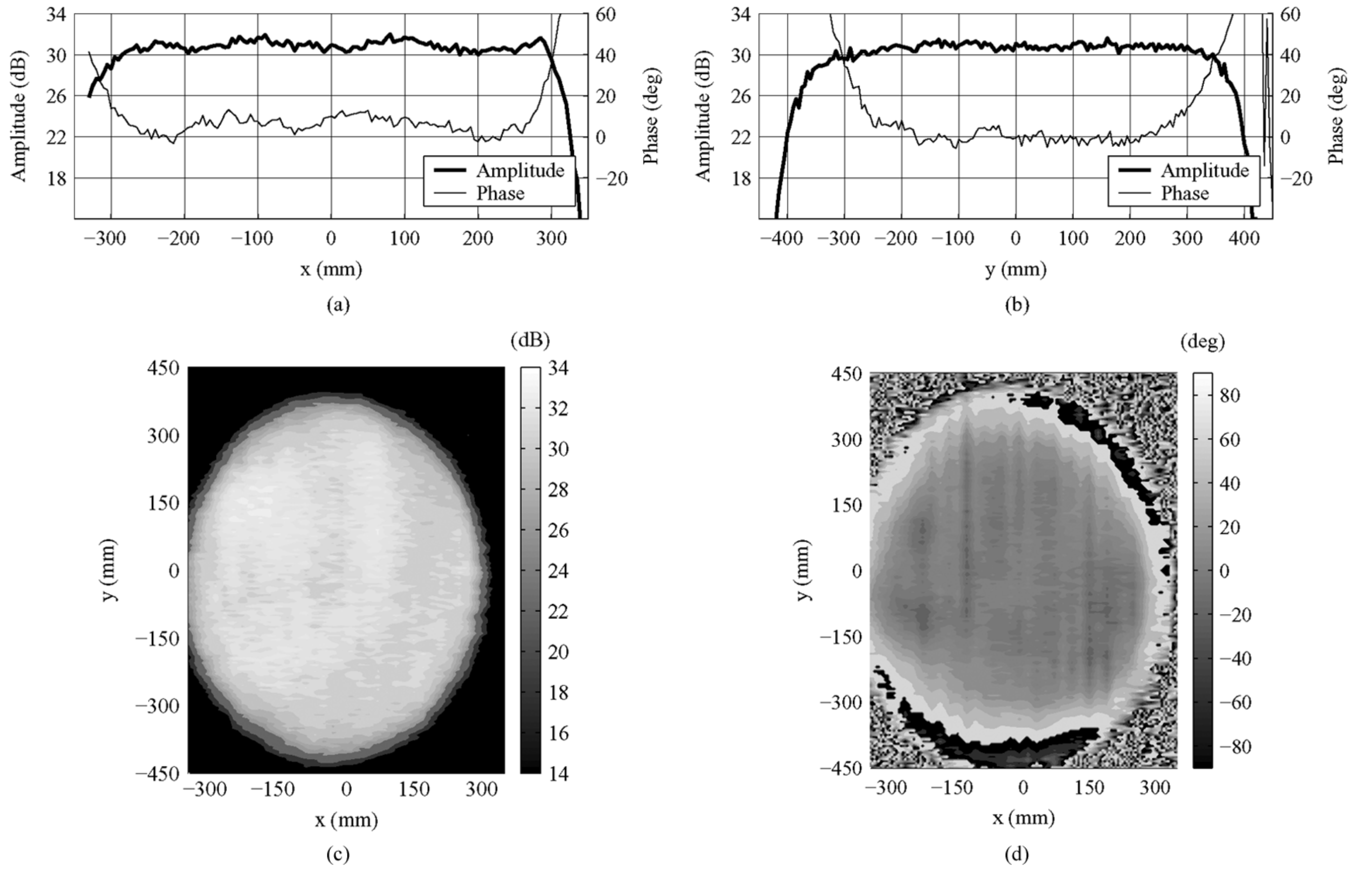

Fig. 6. Hologram II: measured quiet-zone field at 644 GHz at 3 m from the hologram.

TABLE II
MEASUREMENT RESULTS AT 644 GHz

	Hologram I	Hologram II
Peak-to-peak ripples in the horizontal cut	4.0 dB/25°	2.0 dB/15°
Peak-to-peak ripples in the vertical cut	2.0 dB/15°	1.5-2.0 dB/10°
Maximum peak-to-peak ripples in the whole quiet-zone area	4.0 dB/50°	3.0 dB/40°
Size of the quiet-zone (horizontal/vertical direction)	700 mm/870 mm	600 mm/600 mm

The dynamic range is approximately 36 dB for Hologram I and 32 dB for Hologram II. The larger dynamic range is mainly due to wider slots on Hologram I allowing a higher power transmittance through the hologram.

B. Estimate of Measurement Accuracy

The amplitude and phase uncertainties of MVNA at a dynamic range of 32 dB are smaller than 0.35 dB and 1.5° (0.2 dB° and 0.6° at a 36-dB dynamic range, respectively). It was noticed that the measured phase value jittered approximately ±2.5°. This was apparently caused by the phase-locking loop of BWO. Otherwise, measured amplitude and phase values were very stable, and no long-term drifting was seen.

The measured phase values were also affected by the uncertainty of the cable phase error correction system and the planarity error of the scanner. The uncertainty of the cable phase error correction system was estimated to be approximately 5° at 644 GHz. The uncertainty of the laser tracker measurement was approximately 8° at 644 GHz. Therefore, assuming that the planarity of the scanner has remained unchanged during the measurements, the total uncertainty of the measured phase values is less than 17° in the worst case or 10° as rms (values calculated for the 32-dB dynamic range).

VI. DISCUSSION: FEASIBILITY OF THE HOLOGRAM-BASED CATR FOR 650 GHz

The FDTD-based design method was used for designing of two plane-wave-generating holograms for 650 GHz. Comparison of simulation and measurement results shows that the accuracy of this method is also sufficient at higher submillimeter-wave frequencies. One key issue in development of the hologram-based CATR for high submillimeter-wave frequencies is the substrate material. The substrate has to be thin enough so that the field does not resonate inside the substrate. According to this study, the 50-μm-thick Mylar film is an excellent substrate at frequencies up to approximately 650 GHz. After eliminating difficulties encountered in handling the 25-μm-thick Mylar film during the etching process, this film is expected to be suitable for frequencies up to 1000 GHz and above.

Laser writing combined with wet etching is a suitable method to manufacture holograms for submillimeter waves. Overetching of the pattern is a typical manufacturing error, and it causes an amplitude tapering in the quiet-zone field. By carrying out more tests and tuning the manufacturing process to optimum, the systematic manufacturing error could be reduced significantly.

Thus far, the maximum size of a hologram that can be manufactured in one piece with the method used here is 1 m × 3 m. The width of the 25-μm Mylar film used was approximately 1 m and the width of the 50-μm film was 1.35 m. At lower frequencies (119 and 322 GHz), large holograms (diameter > 1 m) have been manufactured from several pieces joining the pieces together by gluing or soldering [8], [14]. Soldering has proven to be a good electrically almost invisible joining method. To achieve a good result, the pieces have to be precisely aligned before joining.

VII. CONCLUSION

Two 1-m-diameter amplitude holograms were designed and manufactured, and they were used as collimating elements in CATR at 644 GHz. The 25- and 50-μm-thick copper-plated Mylar films were found to be suitable substrate materials. Manufacturing method based on direct laser writing of the pattern followed by wet etching was successfully used for processing the holograms. The quiet-zone field generated by the hologram manufactured on the 50-μm film had a higher quality. The measured ripples were only approximately 2 dB and 15°, peak-to-peak for the quiet zone of this hologram. Most likely, the manufacturing quality could be improved by further manufacturing-testing rounds. After this, the hologram-based CATR should also have a high potential at high submillimeter-wave frequencies.

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