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STUDIES ON AN AMPLITUDE HOLOGRAM AS A SUBMILLIMETER-WAVE COLLIMATOR AT CIRCULAR POLARISATION

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ABSTRACT

A hologram can be used as a collimator in the submillimeter-wave compact antenna test range (CATR). Previously, when a horn has been used as the feed, operation of the hologram has been limited to the vertical electric field polarisation. Use of a dual reflector feed system as the feed allows us to design holograms that operate also at the horizontal polarisation. Here, we show by simulations at 310 GHz that the operation of such holograms can be almost identical at both linear polarisations, thus, letting us to assume that these holograms can be used also at the circular polarisation.

1. INTRODUCTION

Holograms can be used to collimate radio waves [1]. We use transmission-type amplitude holograms at millimeter and submillimeter wavelengths to form a plane wave in the compact antenna test range (CATR) [2-4]. Amplitude hologram is a computer-generated interference pattern etched on a thin metal-plated dielectric film. The pattern consists of numerous thin slots and metal strips (see Fig. 1), which are vertically directed and slightly curved. In previous experiments, we have demonstrated the amplitude holograms to be feasible as a collimator at frequencies up to 650 GHz [5].

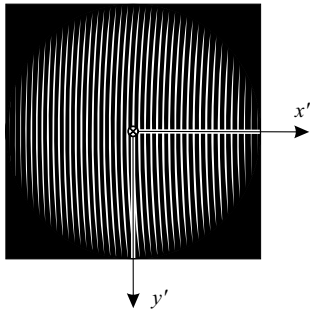


Figure 1. Example of an amplitude hologram pattern.

Fig. 2 shows the hologram CATR setup studied in this paper. As holograms are diffractive gratings, they produce several beams, one of which is the desired plane wave. Usually, we design holograms so that the plane wave emerges from the hologram in an angle of 33° in respect to the surface normal. Absorbing panels are used to terminate the other beams and to eliminate reflections and spillover radiation. A volume of the

plane wave having a highly planar amplitude and phase profile is called a quiet-zone.

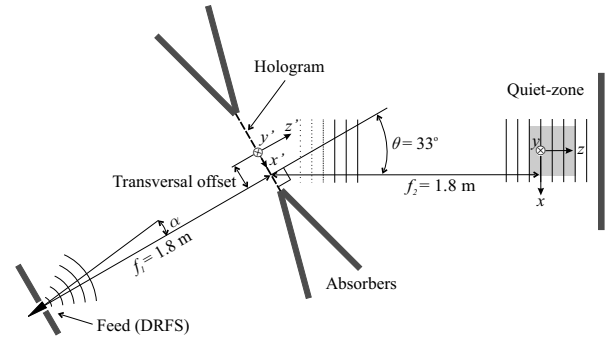


Figure 2. Hologram CATR setup studied in this paper.

Conventionally, a corrugated horn has been used to illuminate a hologram. The horn produces a Gaussian beam, and therefore the field passing through the hologram has to be modified strongly to get a flat quiet-zone amplitude profile. It has been noticed that amplitude modification by tuning slot widths locally in the hologram pattern works well only at the vertical electric field polarisation. Therefore, holograms illuminated with a corrugated horn have always been designed to operate at the vertical polarisation only. In this paper, we use a dual reflector feed system (DRFS) to illuminate holograms [6]. The DRFS we use produces a shaped beam, which has a flat amplitude profile in the middle and a strong tapering on the edges. Its phase front is spherical. As the amplitude of the transmitted field needs not to be modified when the illuminating field is already optimally shaped, a simplified hologram pattern can be used to transform the spherical phase front to a planar one. Some experiments carried out suggest that this kind of a hologram pattern could operate well both at the vertical and horizontal polarisations [7].

In the simulation results presented in [7], there is, however, a significant difference between the quiet-zone amplitude levels at the vertical and horizontal polarisations. The quiet-zone amplitude is approximately 4 dB higher at the vertical polarisation than at the horizontal polarisation. It has been noticed that phase levels at different polarisations can also differ significantly if they are not equalized. In this paper, our

purpose has been to improve the polarisation characteristics of the hologram further, so that it can be used more conveniently, e.g., for antenna measurements at the circular-polarisation.

Perhaps, the most convenient way to obtain the radiation pattern of a (sub-)millimeter wave antenna at the circular polarisation is to measure the radiation pattern (including the amplitude and phase data) at two orthogonal linear polarisations, and to calculate the circular polarisation data from these two components [8]. The two linear polarisations can be, e.g., the vertical and horizontal polarisation. In this measurement method, the quiet-zone amplitude and phase levels do not necessarily have to be the same at different polarisations; the different levels can be taken into account in post-processing. In this paper, however, our goal has been to design a hologram that has an identical operation at the vertical and horizontal polarisation so that the measurements become straightforward and no post-processing corrections are needed.

We start this paper by shortly introducing the simulation method used in the hologram design. Then, we study transmission of a periodic slot structure at 310 GHz, and consider what are the requirements to equalize quiet-zone amplitude and phase levels at different polarisations. We present two holograms designed on different substrate materials and show their co- and cross-polarisation simulation results at 310 GHz. Finally, we consider their use for measurements at the circular polarisation and discuss what things should be studied more carefully in future.

2. SIMULATION METHOD

We use an FDTD (Finite-Difference Time-Domain) based simulation method to optimize holograms [1, 9]. The computer-generated hologram pattern is modified on the basis of simulation results so that the amplitude and phase planarity requirements are fulfilled in the quiet-zone. Typical requirements for the amplitude and phase planarity are that the deviations in the quiet-zone should not exceed 1 dB and 10° , peak-to-peak [10]. These criteria have been used also here in the hologram design. The field transmitted through the hologram is computed with the FDTD method and the quiet-zone field is calculated from this field using physical optics.

The hologram structure has to be simplified so that it can be analyzed with a computer; simulation of an entire hologram pattern would be an enormous task even for super computers. In the FDTD method developed in the Radio Laboratory, the curved slots and strips in the hologram pattern are assumed to be straight and infinitely long in the vertical direction. As the curvature of slots and strips is gentle, the previous simplification can be assumed to lead accurate

simulation results, when the pattern and the field passing through it are examined in the narrow region in the vertical direction, i.e., in a horizontal plane. This simplification enables the use of a two-dimensional FDTD simulation, which requires a fraction of the computational burden needed for the three-dimensional simulation of the entire hologram pattern.

Comparison between simulation and measurement results has shown the two-dimensional simulation method to be accurate enough for the hologram design. In the two-dimensional simulation, two specific cases are studied separately: the polarisation of the illuminating electric field is either vertical (parallel to the slots), or horizontal (perpendicular to the slots). The transmitted field is computed correspondingly either for the vertical, or for the horizontal polarisation and the quiet-zone field is calculated either at the vertical or at the horizontal polarisation by using the corresponding physical optics code. The two-dimensional method can only be used to compute horizontal cuts of the quiet-zone field and it cannot be used to compute cross-polarisation fields. However, a special method has been developed to compute the quiet-zone field in the vertical direction and to estimate cross-polarisation [11]. This method has also been used here in cross-polarisation simulations.

3. TRANSMISSION OF A SLOT STRUCTURE

We start the design of holograms for the circular polarisation by studying the transmission of an infinite periodic slot structure at the vertical and horizontal polarisations. The infinite periodic slot structure can be used to characterize the hologram pattern and its transmission locally. Transmission simulations done for this structure give guidelines on how holograms should be designed so that they operate optimally at both linear polarisations. Simulations are carried out with two-dimensional FDTD codes similar to the ones used in the hologram design. Here, however, only one period of the slot-strip structure is simulated; periodic boundary conditions are used in the sidewalls of the simulation domain to present the periodic structure [11].

Here, we study a slot structure that has a periodicity of $1540\ \mu\text{m}$. This is also the periodicity in the middle of the pattern of Hologram II (see Section 5), which is one of the two holograms designed in this paper. Hologram I, the other hologram designed, has a periodicity of $1480\ \mu\text{m}$ in the middle of the pattern. A $50\text{-}\mu\text{m}$ -thick Mylar film is used as a substrate material behind the slot structure. The substrate material is the same as one used for Hologram II. The structure is illuminated with a normally-incident plane wave.

The transmitted field is simulated at 310 GHz for various slot widths from 20 to $1500\ \mu\text{m}$. The

transmitted field is sampled behind the slot structure. Sampling has to be done at a distance of few wavelengths to avoid reactive near-field effects in proximity of the slot. Here, sampling is done at 5 mm (ca. 5λ) from the slot, where the reactive near field is considered to be negligible. The power transmission at each slot width is calculated by numerically integrating the transmitted power (i.e., the transmitted electric field squared) and comparing it to the power propagating along the plane wave in an empty space.

Fig. 3 shows the simulated transmission graphs in dB versus the slot width. It can be seen that at both polarisations, the transmission tends to $-\infty$ dB as the slot width approaches zero, and to 0 dB as the slot width approaches the period length, i.e., when the metal strip width approaches zero, a transmission loss of 0.5 dB remains in the graph due to the reflection loss from the Mylar film.

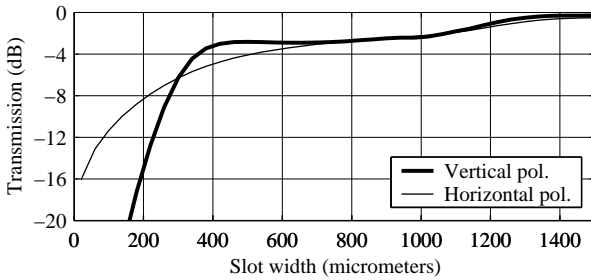


Figure 3. Simulated transmission of an infinite periodic slot structure at 310 GHz at the vertical and the horizontal polarisations.

At slot widths up to 400 μm , the transmission in respect to the slot width increases rapidly at both polarisations, and after that the increase becomes very slow. At slot width larger than 555 μm , the deviation between the transmissions at different polarisations is less than 1 dB, and at slot widths larger than 645 μm , the deviation decreases to 0.5 dB. According to this study, the slot widths should approximately be larger than 600 μm so that the transmissions at different polarisations can be equalized. The transmission graphs differ slightly from the ones presented in Fig. 3 when simulations are performed for the 25 μm Mylar film, which is the substrate of Hologram I.

As there are many factors not taken account in the previous study but that have a significant influence on operation of the hologram, the transmission graphs presented in Fig. 3 can only be used as a base for the actual hologram design. For example, in a more accurate analysis, it should be taken into account that the periodicity of the hologram pattern is not constant

over the pattern but varies significantly (e.g., between 1230-2090 μm in Hologram II), which can also change transmission. In addition, the wave illuminating the hologram is not really a plane wave having a normally incident angle but a spherical wave having an oblique incident angle. The periodicity of the pattern and the slot width has also some influence on the phase of the transmitted field, which should be taken into account in the accurate analysis.

4. DUAL REFLECTOR FEED SYSTEM

Conventionally, we have used corrugated horns to illuminate holograms. As the corrugated horn has a Gaussian beam, the amplitude of the transmitted field has to be modified by tuning the slot widths locally. The Gaussian amplitude profile can be eliminated by narrowing slots properly in the middle of the pattern and the disturbing edge diffraction caused by a high edge illumination can be reduced by narrowing slots towards the edges of the hologram [1]. According to Fig. 3, the slot widths have to be smaller than 400 μm so that the amplitude of the transmitted field can be controlled by tuning the slot widths. Unfortunately, as can be seen from Fig. 3, the transmissions at different polarisations deviates at small slot widths, and therefore the quiet-zone fields at different polarisations cannot be equalized when a corrugated horn is used as the feed.

The slots have to be very wide to equalize the transmission of the hologram at both polarisations. This is possible only when a shaped beam is used to illuminate the hologram. The illumination has to have a flat amplitude profile in the middle and a strong tapering on the edges so that the amplitude of the transmitted field needs not to be modified. In that case, the hologram is used only to transform the spherical phase front to a planar one.

A shaped illumination can be produced with a dual reflector feed system (DRFS), which modifies the radiation pattern of a corrugated horn used as the primary feed of the system. A prototype DRFS has been designed and constructed for 310 GHz and has already been used as the feed in some hologram-CATR setups [6, 7]. This DRFS produces a 5-th order Butterworth-type beam with a spherical phase front. The DRFS is designed to illuminate 600-mm-diameter holograms but it can be used also with other sized holograms if the focal length versus the diameter of the hologram (i.e., f/D ratio) remains reasonable. The focal length is designed to be 1.8 m for 600-mm-diameter holograms, i.e., $f/D = 3$. When the DRFS is placed at a distance of 1.8 m from a 600 mm hologram, the -1 dB beam width of the illumination is 370 mm and the edge illumination is ca. -15 dB. Fig. 4 shows the ideal DRFS illumination that has been used in the hologram design in this paper. According to measurements, the actual DRFS beam

differs only slightly from the ideal one [6]. The DRFS illumination remains unchanged when the polarization of the feed horn is turned by 90° .

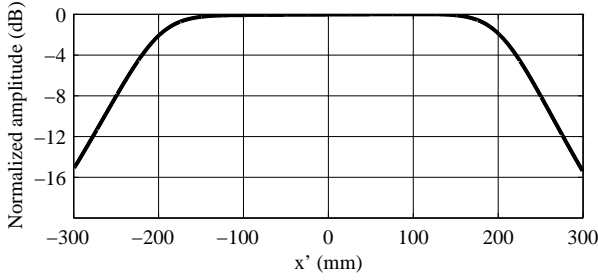


Figure 4. DRFS illumination at 310 GHz in the hologram plane at a distance of 1.8 m.

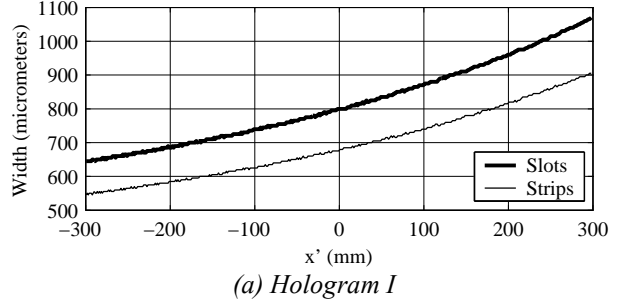
5. HOLOGRAMS DESIGNED

Two 600-mm-diameter holograms were designed for the 310 GHz DRFS illumination. Their operation at different polarisation was optimized to be as identical as possible. To see if the substrate material has some effect on the operation, one hologram was designed for the 25- μm -thick Mylar film (called Hologram I) and the other for the 50- μm -thick Mylar film (called Hologram II). These films have already been used as substrate materials in previous holograms [3, 5].

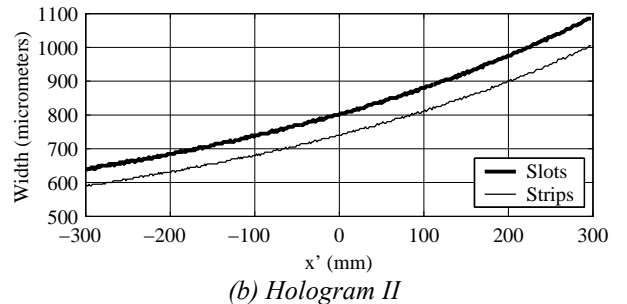
The DRFS was placed at a distance of 1.8 m and the quiet-zone was optimized at 1.8 m from the holograms (see Fig. 2). It was noticed that the thicker film has a stronger effect on the operation of the hologram than the thinner film has, and therefore optimization of Hologram II was slightly more difficult than optimization of Hologram I. The period length increases towards the right edge of the hologram pattern. The variation can be reduced by moving the feed from the optical axis to the right in the transversal direction (see Fig. 2). A smaller variation of the period length makes the optimization of the quiet-zone field easier. It was noticed that the optimal location of the feed depends on the thickness of the film. For Hologram I, the optimal location of DRFS was found to be at a distance of 200 mm from the optical axis. The DRFS needs to be turned by 6° towards the centre point of the hologram so that the illumination stays centered on the hologram. For Hologram II, the optimal parameters were found to be 149 mm and 4.7° , respectively.

Fig. 5 shows the designed slot and metal strip widths along the horizontal centerline of Hologram I and II. On Hologram I, the slot widths vary between 650–1070 μm , and the metals strips vary between 550–900 μm . On Hologram II, the slot and metal strip widths vary between 650–1100 μm and 600–1000 μm , respectively. The slots are approximately 2.5 times

wider than the slots of holograms designed for the same frequency earlier [6], and they are even wider than the metal strips, which has not been possible when a Gaussian beam has been used to illuminate holograms. It has been considered that large slot widths can result in a very low cross-polarisation level.



(a) Hologram I



(b) Hologram II

Figure 5. Slot and metal strip widths along the horizontal cut of a) Hologram I (on 25 μm Mylar film), and b) Hologram II (on 50 μm Mylar film).

5.1 Simulated Quiet-Zone Field

Figs. 6 and 7 show the simulated quiet-zone fields of Hologram I and II, respectively. It can be seen that for both holograms the quality of the quiet-zone field is very good at both polarisations. The quiet-zone amplitude and phase are almost independent of the polarisation, which was our goal. The phase is slightly (by 10°) tilted for both holograms at the vertical polarisation. This means that at the vertical polarisation, the propagation direction of the plane wave differs slightly from the designed propagation angle (33°) that was used in physical optics. It has been found that the precise propagation angles at the vertical polarisation are 32.9955° and 32.9950° for Hologram I and II, respectively. When the quiet-zone fields at the vertical polarisation are calculated at these angles, the resulting phase curves coincide almost perfectly with the phase curves calculated at the horizontal polarisation at the angle of 33° . Excluding the 10° -phase slope, the peak-to-peak amplitude and phase deviations at both polarisations are approximately 0.5 dB and 4° for Hologram I, and 0.7 dB and 4.5° for Hologram II, respectively.

The -1 dB beam width of DRFS limits the size of the quiet-zone. In the vertical direction, the width of the quiet-zone should be the same as the -1 dB beam width of DRFS, i.e., 370 mm. In the horizontal direction, the width of the quiet-zone is reduced by the oblique propagation angle. The theoretical value, $370 \text{ mm} \times \cos(33^\circ) = 310 \text{ mm}$, agrees very well with the simulation result.

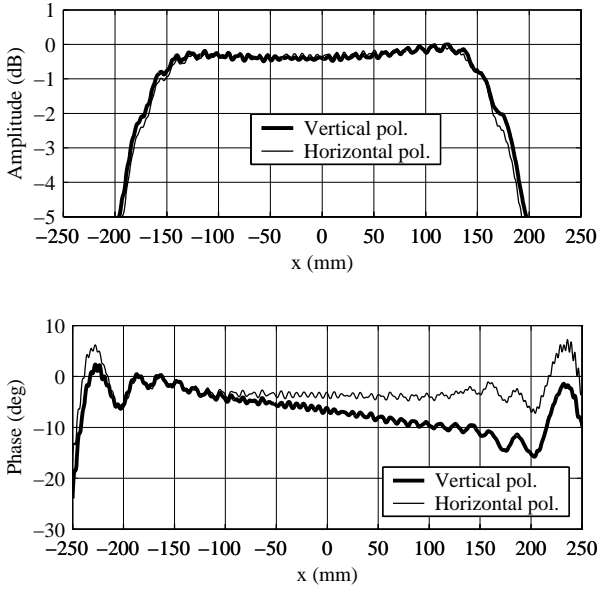


Figure 6. Simulated quiet-zone field of Hologram I (on $25 \mu\text{m}$ Mylar film) at 310 GHz.

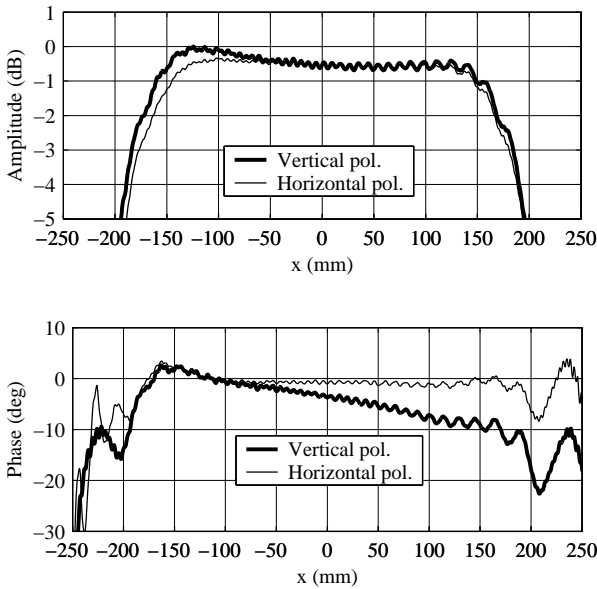


Figure 7. Simulated quiet-zone field of Hologram II (on $50 \mu\text{m}$ Mylar film) at 310 GHz.

5.2 Simulated Cross-Polarisation

It has been estimated that wide slots can result in a very low cross-polarisation level. Fig. 8 shows the simulated cross-polarisation in the vertical direction at different main polarisations. It can be seen that the cross-polarisation behaviour is very similar at both polarisations and for both holograms. The maximum cross-polarisation level on the edge of the quiet-zone is -26.8 dB for Hologram I, and -26.3 dB for Hologram II. The cross-polarisation level of these holograms is approximately 10 dB lower than that of conventional holograms designed for Gaussian illumination.

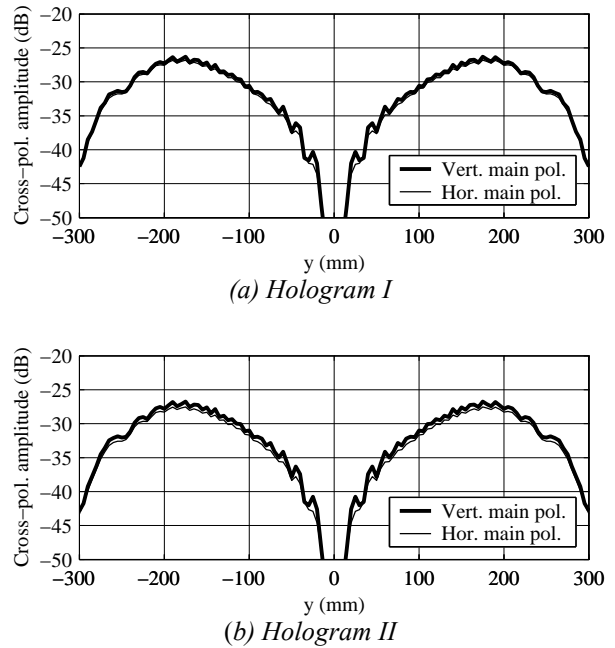


Figure 8. Simulated cross-polarisations in the vertical cut at 310 GHz at different main polarizations.

6. DISCUSSION AND FUTURE WORK

Very promising results have been achieved in this work. According to the simulation results, a hologram can be designed to operate almost identically at both linear polarisations, and therefore it can be used readily also for circular-polarisation measurements. A small deviation (ca. 0.005°) between the plane wave propagation angles at different polarisations can be taken into account in the post-processing of antenna measurements if seen necessary.

Hologram II (on $50 \mu\text{m}$ Mylar film) has already been manufactured and its operation is going to be tested soon. It should be studied further what kind of effects potential manufacturing errors can have on the operation at different polarisations. The most typical manufacturing error is systematic under- or over-etching of the pattern. Systematic manufacturing error has most

likely a different effect on the transmission at the vertical and horizontal polarisations.

Quiet-zone testing can be a rather challenging task. The polarisations of the transmitting and receiving horns can be turned by twists or by rotating the complete receiver and transmitter blocks. If twists are going to be used, the loss and the phase difference caused by the twists have to be known accurately so that they can be eliminated from the measurement results.

7. CONCLUSION

In this paper, we studied how a transmission-type amplitude hologram can be designed to operate identically at the vertical and horizontal electric field polarisations so that it could be used readily for antenna measurements at the circular polarisation. It was found that such a hologram is possible to design when a dual reflector feed system (DRFS) is used to illuminate the hologram. Two demonstrative holograms were designed for two different Mylar substrates. The simulation results show that these holograms operate very well and almost identically at both linear polarisations. Also, cross-polarisation of these holograms was simulated. According to simulation results, the maximum cross-polarisation level of these holograms at both main polarisations is less than -26 dB, which is approximately 10 dB lower than that of previous holograms.

8. ACKNOWLEDGMENT

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