ON THE DESIGN OF SUB-MM WAVE AMPLITUDE HOLOGRAMS FOR CATR

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Abstract – A compact antenna test range (CATR) based on a 3 m hologram has been designed in order to measure the ESA ADMIRALS test antenna at 322 GHz. Also, a 650 GHz demonstration CATR based on a 0.97 m hologram has been designed. Both CATRs will be realized and tested later in 2002. In this paper, the design of the CATRs is discussed and simulation results are presented.

1. INTRODUCTION

Several ongoing projects (e.g., Planck and Herschel) aim to construct scientific or remote sensing satellites to probe the Universe at sub-mm wavelengths. These satellites will carry on board electrically very large reflector antennas, which should be tested before launch. The measurement of the antenna radiation pattern is perhaps the most essential test. Current measurement methods have significant weaknesses at sub-mm wavelengths, and hence a lot of work has and will be done in developing the current methods and inventing new ones.

The most suitable method to measure a full-radiation pattern at sub-mm wavelengths appears to be the compact antenna test range (CATR) [1]. This is because of its simple use in measurements. The radiation pattern of an antennaunder-test (AUT) can be measured directly as in the far-field method, which is widely used at lower frequencies. At sub-mm wavelengths, the far-field method is ruled out due to the very long measurement distance needed. For large reflector antennas, the distance may be even dozens of kilometers, which raises the atmospheric attenuation to a non-permitted level. One antenna testing method that can be used in the sub-mm wave range is a near-field scanning [2]. However, large amounts of near-field data have to be acquired that extends the measurement time very long (even to several days), and thus a high stability of measurement system is required. In a CATR, a spherical wave radiated by a feed antenna, e.g., a horn is transformed to a plane wave with the use of a focusing element. The plane wave is used to measure the radiation pattern of the AUT. Since the dimensions of the range are relatively small, the CATR can be situated indoors and problems caused by the atmosphere are avoided. The AUT is placed into the quiet-zone (QZ), which is a region of the plane wave where the field quality satisfies certain criteria. Typical criteria for the plane wave in the QZ are that the amplitude and phase ripples 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 2–3 reflectors. In the sub-mm wave range, a strict surface accuracy requirement $(\sim\lambda/100)$ makes the manufacturing of large reflectors very difficult and highly expensive. The focusing element could be also a lens, which has a lower surface accuracy requirement compared to a reflector (by a factor of $(\sqrt{\varepsilon_r} - 1)/\sqrt{2}$ lower). However, finding an appropriate low-permittivity, high-homogeneity material is difficult.

2. HOLOGRAM BASED CATR

We use a hologram as the focusing element [3]. As the hologram is a transmission-type element its surface accuracy requirement ($\sim \lambda/10$) is much lower than that of a reflector. Layout of a hologram based CATR is shown in Figure 1. When the hologram is illuminated with a horn antenna it diffracts several beams into different directions. One of the beams is the desired plane wave used in antenna testing. The hologram is designed so that the plane wave propagates in an angle of 33° with respect to the normal of the hologram. This prevents the other diffraction modes produced by the hologram to disturb the QZ –field. Unwanted beams and the direct radiation of the horn antenna are eliminated by absorbers. Distance between the hologram and the horn is typically 2-5D (diameter of the hologram is D) and the QZ –field is optimized at a distance of 2-5D.

The hologram used in a CATR is the interference pattern of a spherical wave and a plane wave coming from a certain direction (i.e., 33°). A binary amplitude hologram is a slot pattern, which has been etched onto a metal layer on top of a thin dielectric film. Holograms described more in detail later in this paper will be fabricated using the laser exposure of pattern and chemical wet-etching. High flatness is ensured by tensioning the hologram to a stiff frame. An example of a binary amplitude hologram is shown in Figure 2 where nearly vertical, radiotransparent slots are in white and metal stripes between them in black. The widths of the slots are less than 0.5λ . The slots have been tapered (narrowed) towards the edges of the hologram to prevent harmful edge diffraction.



Figure 1. Layout of a hologram based CATR.



Figure 2. Binary amplitude hologram pattern.

The binary hologram pattern is generated with computer. Due to several nonidealities (e.g., a dielectric film, an edge diffraction and a non-ideal transmittance of slots), the initial hologram pattern does not directly produce a QZ adequate for antenna measurements. Therefore, the detailed electromagnetic behavior of the hologram structure has to be analyzed and the performance of the hologram optimized. Fields within the hologram structure and in the aperture are computed using the Finite-Difference Time-Domain (FDTD) method. The QZ –field is calculated from the aperture field using physical optics. If the QZ –field does not fulfill the requirements, the hologram pattern is modified appropriately and a new simulation is done. This iterative procedure is repeated until a satisfactory result is achieved. If the width of a slot is at max. 0.4λ , the transmitted power of a vertically polarized wave is a monotonically increasing function of the width. Then, the amplitude of the QZ –field can be easily modified narrowing/widening the slots. The phase can be tuned moving the slots slightly. A local modification of the pattern affects (almost only) locally the QZ –field that makes the optimization of the QZ –field quite straightforward. The transmission coefficient of a slot is polarization dependent. For a horizontally polarized wave, the transmitted power is not a monotone function of the slot width, and hence it's very difficult to design holograms for the horizontal polarization. Therefore, holograms are always designed for a vertically polarized incident electric field.

Since the hologram is electrically very large, simulation of a whole hologram would be a too massive operation even for supercomputers. Comparisons between simulation and measurement results have shown that with a good accuracy the hologram pattern can be assumed to be infinite in the vertical direction when the QZ –field is examined locally along a horizontal cut. This is due to the gentle curvature of slots in the vertical direction. The assumption enables the use of a two-dimensional FDTD simulation, which reduces the computational burden to a fraction of the original one. Figure 3 illustrates the simplification of the analyzed structure. A hologram grid is generated at a certain y coordinate and the structure is assumed to be infinite in the y direction. Then, a two-dimensional FDTD simulation is done and the QZ –field is calculated at the same y coordinate. In a two-dimensional FDTD simulation, two cases can be studied separately: the incident electric field is either horizontally or vertically polarized. However, only an analysis for the vertically polarized electric field is usually done. [4]



Figure 3. Simplification of a hologram used in FDTD simulations.

The simulation of cross-polarization is not possible when the simplification is done and the curvature of slots is omitted. The numerical simulation of crosspolarization has been examined in [5]. Results from FDTD simulations and measurements agreed very well. The typical cross-polarization level of a hologram is about -20 dB near the edges of QZ. At the horizontal centerline, the cross-polarization is very small.

3. DESIGN OF HOLOGRAM BASED CATRs FOR 322 GHz AND 650 GHz

In our ongoing ESA project, two sub-mm wave CATRs based on binary amplitude holograms will be constructed. Both CATRs have been already designed and they will be realized and tested later in 2002. One of the CATRs is going to be used to measure the ESA ADMIRALS test antenna at 322 GHz. The diameter of the test antenna is 1.5 m. It has been estimated that to measure the antenna properly the diameter of the QZ has to be at least 1.8 m. The FDTD simulations show that a 3 m wide hologram produces a QZ larger than 1.8 m and is thus appropriate. Since there is no 3 m wide dielectric film available the hologram has to be composed of three 1×3 m² horizontal pieces. The pieces will be etched separately and then joined together by soldering. Numerous experimental studies carried out show that the soldering is the best choice to join pieces together. Also, taping and glueing were tested but the performance of the hologram was much worse with them. Furthermore, it has been noticed that a horizontal joint causes much less distortion than a vertical one. Careful alignment of the pieces is important to avoid an additional distortion. This hologram will be etched onto a 50 μ m Mylar film covered with $17 \ \mu m$ thick copper layer. The distance from the horn to the hologram is 9 m and the QZ is optimized at a distance of 9 m from the hologram. The simulated QZ -field of the 322 GHz hologram at y = 0 at a distance of 9 m from the hologram is shown in Figure 4. Transversal displacement in the QZ is denoted by x. The width of the QZ is more than 1.95 m. The amplitude and phase ripples are less than 0.5 dB and 5°, peak-to-peak, respectively.

The other CATR is smaller and it will be used to demonstrate the feasibility of the hologram CATR at higher frequencies. The diameter of the hologram is 0.97 m and the operating frequency is 650 GHz. The diameter is limited by the maximum width of the suitable film. The hologram will be etched in a single piece onto a 25 μ m Mylar film covered with 5 μ m thick copper layer. The thickness of the film has to be reduced to 25 μ m to avoid internal reflections inside the film. The distance from the horn to the hologram is 3 m and the QZ is optimized at a distance of 3 m from the hologram. The simulated QZ –field of the 650 GHz hologram at y = 0 at a distance of 3 m from the hologram is shown in Figure 5. The width of the QZ is more than 0.6 m. The amplitude and phase ripples are less than 0.5 dB and 5°, peak-to-peak, respectively.



Figure 4. Simulated QZ -field of the 322 GHz hologram at y = 0 at a distance of 9 m from the hologram



Figure 5. Simulated QZ -field of the 650 GHz hologram at y = 0 at a distance of 3 m from the hologram.

4. CONCLUSIONS

Two sub-mm wave CATRs based on binary amplitude holograms have been designed and simulated. They will be realized and tested later in 2002. The large CATR is based on a 3 m hologram and it will be used to measure the 1.5 m ESA ADMIRALS test antenna at 322 GHz. The other CATR is based on a

0.97 m hologram and operates at 650 GHz in order to demonstrate the feasibility of the hologram CATR at wavelengths under 0.5 mm.

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