Performance analysis of a submillimeter wave hologram CATR

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Abstract–A hologram is a planar, transmission type of collimating component. Performance of a submillimeter wave hologram type of compact antenna test range (CATR) is studied with a combined analysis of a physical optics (PO) and a finite difference time domain (FDTD) method at 500 GHz. Main focus is on the fabrication errors, the feed positioning errors, and the frequency and polarization dependence of the hologram structure. The effect of planarity errors is discussed.

1. INTRODUCTION

Theoretical and experimental analyses have shown that a hologram type of compact antenna test range (CATR) is a potential way of realizing a high-quality plane wave for antenna testing at millimeter wavelengths [1,2,3]. A hologram is a planar, transmission type of collimating component. Thus, the surface accuracy requirements for an amplitude hologram are less stringent than those for a reflector, which is the traditional collimating element in compact antenna test ranges. The surface accuracy of a CATR reflector needs to be better than about 0.01 wavelengths which leads to very tight surface accuracy specifications at submillimeter wavelengths. A recent study shows that both a reflector and a hologram CATR are feasible at submillimeter wavelengths, but the reflector needed is very expensive [4]. A hologram is a low-cost, easy-to-fabricate, structure. As a result, a hologram CATR has great potential for realizing high-quality, low-cost, compact ranges, even at submillimeter wavelengths.

Figure 1 illustrates a facility layout employing a hologram CATR and an example of a hologram pattern. In a hologram CATR, the feed horn transmits a spherical wave onto one side of a computer-generated amplitude hologram structure which modulates the field such that a planar wave is emanated on the other side of the structure. The extent of the volume enclosing the plane wave is called the quiet-zone. Typical requirements for the quiet-zone field are an amplitude ripple less than 1 dB and a phase ripple less than 10°. The hologram pattern is determined by numerically calculating the structure required to change the known input field into the desired output field. The hologram consists of narrow curved slots in a conducting plane where the phase is modulated by the locations of the slots and the amplitude is modulated by the variations of the slot widths. The plane wave is designed to leave the hologram in a certain angle (e.g. 33°) in order to separate the wanted plane wave from the unwanted diffraction modes generated by the hologram [2,5]. Holograms for compact ranges are fabricated on a metal plated dielectric film using a standard etching procedure.

In this paper, the theoretical basis of the analysis is briefly reviewed. The performance analysis includes the effects of the: 1) fabrication errors of the hologram pattern (i.e. errors in the widths of the slots), 2) axial, transverse, and rotational displacement of the feed, 3) frequency change, 4) polarization change, and 5) the joint between the parts of the hologram. The effect of the planarity errors is discussed. In order to keep the simulation time reasonable, the diameter of the hologram in these analyses is 200 mm at 500 GHz. The optimization of the 200 mm diameter hologram which is used in the analyses is reported in [6].

2. ANALYSIS METHOD

The theoretical analysis is based on the finite difference time domain (FDTD) method and the physical optics (PO). FDTD is used for calculating the transmission of the narrow slots of the hologram. The transmission depends on the polarization of the field and the width of the slot. The excitation is directly the feed horn amplitude and phase pattern on the surface of the dielectric film. The result of the FDTD analysis is the amplitude and phase in the plane of the metal. These field values are the aperture field values in the PO calculation which results the quiet-zone field.

A full simulation of the wave interactions in the plane of the hologram with the FDTD is impossible due to very large size of the structure. Therefore, some simplifications have to be made. Measurements at 119 GHz have verified that it is sufficient to analyze only one cut of the hologram, when the quiet-zone field is analyzed in the same *xz*-plane where the cut has been taken. When only one cut of the hologram is analyzed, an assumption, that the geometry does not change in the y-direction, has to be made. This kind of simplified structure can be simulated with a two-dimensional FDTD [2,3].

The theory of the computer-generated holograms and the combination of PO and FDTD are used when the hologram structures for CATRs are optimized. The widths of the slots and the distances between the slots depend on the frequency, the characteristics of the feed antenna, the dimensions of the CATR, and the design of the hologram itself. The hologram design is necessarily an iterative procedure, because the aperture field (in the plane of the metal) is not known before the hologram is generated. Generally, the structure of the hologram is optimized for a single frequency and a linear polarization to produce a plane wave at a certain distance from the hologram. In this case, the hologram was optimized for vertical polarization, and widths of the slots are 20–260 μm [6]. In this paper, the structure of an optimized hologram is modified in order to simulate the fabrication errors and the changed quiet-zone fields at vertical polarization are calculated.

3. FABRICATION ERRORS OF THE HOLOGRAM PATTERN

Holograms for compact ranges are fabricated on a metal plated dielectric film using a standard etching procedure. Fabrication errors are due to the inaccuracies of the three main steps in the fabrication procedure: 1) mask (inaccuracy of the plotter and the limited size of the graphics file), 2) pattern transfer, and 3) etching. Furthermore, the fabrication errors may be divided into systematic errors and random errors. Due to systematic fabrication errors, all the slots of the hologram are wider or narrower than in the ideal case. Because of the random errors the slots are randomly either wider or narrower than in the ideal case. The order of magnitude of the systematic errors due to each of the three steps of the fabrication procedure may be estimated at 10 μm in the width of the slot. This means that collimated light has to be used in the pattern transfer, and a dielectric film with a 5 μm thick metal layer has to be used for the hologram. In total, this means that ±30 μm is the worst case, and ±17 μm is the RSS case. Random errors are considered to be mainly due to the limited size of the graphics file or the resolution of the precision printer, and it means that the edges of the curved slots are serrated instead of being smooth. This error is not exactly random but may well be estimated with a normally distributed random error in the widths of the slots. Ultimately, the resolution of the printer determines the random error. 2000 dots per inch is available in Finland (12.7 μm point separation) which means less than 5 μm standard deviation of the normally distributed random error.

In the analysis, the widths of the slots were changed by ±10 μm, ±20 μm, ±30 μm, and ±50 μm. The standard deviation in the case of random errors was 5 μm, 10 μm, and 20 μm. As an example, Figure 2a shows the effect of systematic fabrication errors of a 200 mm diameter hologram on the quiet-zone field compared to the ideal case at 500 GHz. The amplitude and phase curves have been vertically shifted in order to separate them from each other. The effect of a specific error depends on the frequency, the geometry of the facility (i.e. the focal length and the diameter of the hologram), and the distribution of the slot widths. However, the results obtained for small holograms should give a realistic estimation of the feasibility of a submillimeter wave hologram CATR. Systematic fabrication errors increase slightly the quiet-zone ripple and change the size and shape of the quiet-zone. The relative change of the quiet-zone size in a case of a small hologram is large. The effect of the systematic fabrication errors on the RMS phase ripple of the quiet-zone is almost negligible if the relative change of the slot width is small, also reported in [4]. Nevertheless, large (relative to the wavelength) systematic fabrication errors may change dramatically the field distribution in the quiet-zone [7]. However, the systematic fabrication error can be measured and compensated when a new mask is generated assuming the systematic error is the same all over the hologram and in the succeeding fabrication procedure. Random errors increase the amplitude and phase ripple in the quiet-zone, and the highest possible resolution of the printer should be utilized. Figure 2b shows the quiet-zone field in the case of a normally distributed random error with $\sigma = 5$ μm at 500 GHz.

4. FLATNESS ERRORS

The flatness errors of the hologram have not been theoretically analyzed. High planarity can be achieved, when the hologram film is stretched on a frame. The local extensions of the film, which remain unchanged when the film is stretched, are a possible source of error. On the basis of measurements at 119 GHz, small dot-like extensions have a negligible effect on the quiet-zone field. Large (area ≥ square of the wavelength), visible extensions affect the quiet-zone field, but it is difficult to give any exact numbers. However, a hologram is a transmission type of focusing element, and it can have twice the surface error compared to a reflector. An added advantage is shown in Figure 3. The lower part of the figure, a hologram with surface error, shows that distances have become shorter, but the shortening of these electrical lengths is partly compensated, because the incoming wave travels a longer way on the other side. Thus, the planarity error is not assumed to be the main problem, especially, if the hologram is handled with care [4].

5. FEED POSITIONING ERRORS

The main effect of the (small) transversal feed displacement is the change in the direction of the plane wave. The main effect of the axial feed displacement is the phase distribution becoming curved. Furthermore, the size of the quiet-zone is slightly changed due to changed illumination of the hologram. The main effect of the rotational displacement is an amplitude tilt in the quiet-zone. From the different feed displacements the effect of the rotational displacement is the most distinct, because it clearly affects the amplitude. In the hologram quiet-zone measurements, the position of the feed is tuned by measuring the quiet-zone field and comparing it to the theoretical value. After this tuning the position is assumed to be correct.

6. BANDWIDTH OF A HOLOGRAM CATR

Because the locations of the slots are determined by the phase of the incoming field, a hologram is a frequency dependent component. The useful bandwidth is case-specific, i.e., it depends on the size of the hologram compared to the wavelength, the focal length, the aperture weighting function, and the feed antenna. The most distinct effect of a frequency change is the change in the direction of the plane wave according to $\theta = \arcsin(\nu\lambda)$, where ν is a spatial carrier frequency needed to separate the plane wave from the unwanted diffraction modes [2], and λ is the wavelength. Other effects are the increased amplitude and phase ripple in the quiet-zone and phase distribution in the quiet-zone becoming curved, instead of being flat. These effects are due to the changes in the radiation pattern of the feed antenna and in the transmission coefficients of the slots due to the changed wavelength. The phase curvature can be compensated with an axial feed movement, while the quiet-zone amplitude and phase ripple remain almost unchanged. Ultimately, the useful bandwidth depends on the requirements of the quiet-zone amplitude and phase ripple. Figure 4a shows the quiet-zone field of the 500 GHz hologram at 450, 500, and 550 GHz where the phase curvature has been compensated with the axial feed movement: 6 cm towards the hologram at 450 GHz and 6 cm further away from the hologram at 550 GHz. The bandwidth of this hologram is less than ±10 %.

7. POLARIZATION DEPENDENCE

The transmission of the hologram depends on the polarization of the incoming field and the widths of the slots [2,3]. Thus, the quiet-zone field necessarily depends on the polarization, especially, if the amplitude tapering of the aperture field is realized with the hologram structure by making the slots very narrow at the edge which is the case in this hologram. Figure 4b shows the quiet-zone fields at vertical (optimized) and horizontal polarizations. A possible solution for reducing the polarization sensitivity would be the use of small sub-reflectors so that the necessary tapering is realized by the feed. This possibility will be studied further in the future.

8. FABRICATION FROM SEVERAL PIECES

The fabrication of a large hologram is currently a problem. If the hologram is made by joining several pieces together, the joints are a problem because due to the joint, a small gap is introduced when the hologram is stretched. Figure 4c shows the effect of a 100 μm wide vertical gap on the quiet-zone field at 500 GHz. The magnitude of the amplitude and phase errors depend on the width of the gap. Because of a gap in the direction of the slots (i.e. vertical in this case), the parts of the hologram are 'out of phase' resulting an erroneous quiet-zone field. Vertical gaps in the hologram structure have been found to be very undesirable (theoretically and experimentally) also in the development of the 2.4 m × 2.0 m hologram for the Odin telescope tests at 119 GHz. The effect of horizontal gaps is much less critical. The largest size of a high-precision print, which is the mask in the pattern transfer, is 1.2 m × 1.0 m (available in Finland), and 1.0 m wide copper plated Mylar is available. Several masks can be joined together in the pattern transfer. Thus, the limiting factor in the fabrication is the pattern transfer and etching processes. Silk-screen printing can be used up to about 100 GHz but at higher frequencies the inaccuracies of the process are too large. A 60 cm × 60 cm patterns can be fabricated with more accurate etching processes (available in Finland).

CONCLUSION

Feasibility of a submillimeter wave hologram CATR is studied with a combined analysis of a physical optics (PO) and a finite difference time domain (FDTD) method. A hologram CATR is a low-cost alternative for the conventional reflector compact range. Due to less stringent surface accuracy requirements, a hologram CATR constitutes an effective method for measuring electrically large millimeter and submillimeter wave antennas. The fairly strong frequency and polarization dependence are the disadvantages of the hologram CATR. Ways of reducing the polarization dependence and the analysis of the effects of the planarity errors are subjects for the future studies. The fabrication of the large holograms needs further development. The tolerance requirements of a submillimeter wave hologram are not too stringent for the fabrication techniques that are used for making printed circuits. The problem is that the present day fabrication techniques are not capable of fabricating large structures. However, a hologram CATR is seen as a method which has great potential for testing electrically large submillimeter wave antennas.

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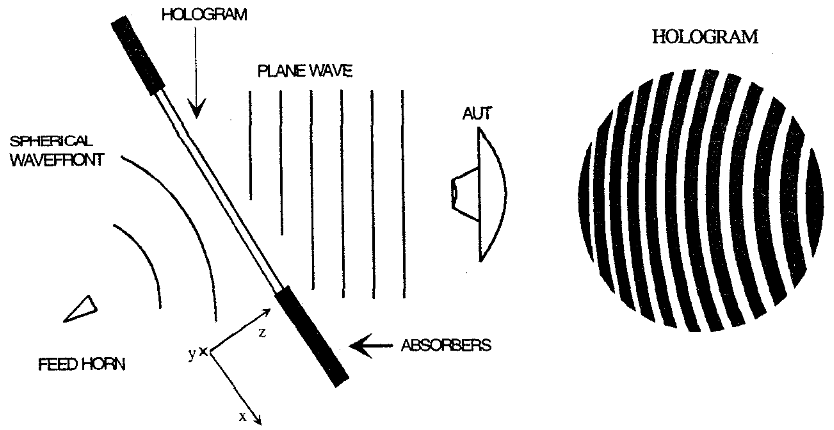

Figure 1. Hologram CATR and an example of a hologram pattern.

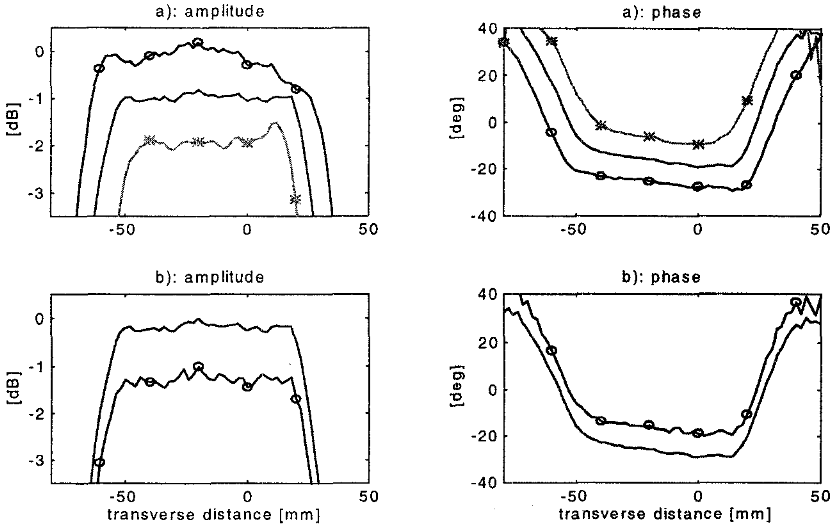

Figure 2. a) Effect of the ± 30 μm systematic fabrication errors at 500 GHz: ideal case, + 30 μm (o) and – 30 μm (*), b) effect of the random error at 500 GHz, $\sigma = 5$ μm (o).

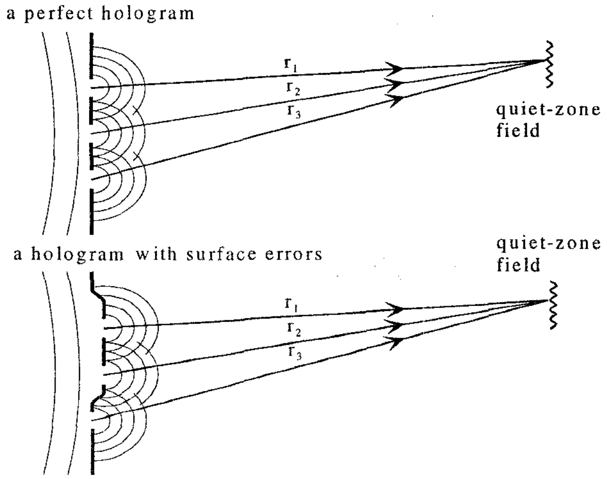

Figure 3. A side view of a perfect hologram and a hologram with surface errors.

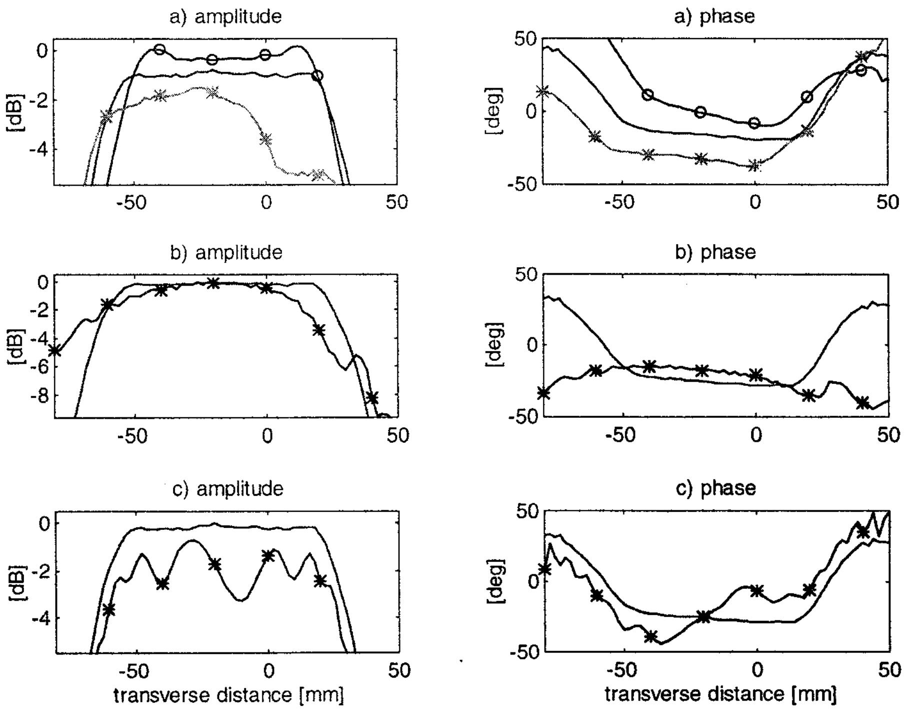

Figure 4. a) Quiet-zone field at 450 (o), 500, and 550 (*) GHz. **b)** Polarization dependence: quiet-zone fields at vertical and horizontal (*) polarizations. **c)** Effect of a 100 μm vertical gap on the quiet-zone field at 500 GHz.