Radio-wave Beam Shaping using Holograms

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Abstract — **Millimetre-wave radio fields are shaped using both amplitude- and phase-type computer-generated holograms (diffractive elements). Methods for hologram element synthesis are described. Holograms that produce plane waves, radio-wave vortices, and Bessel beams at 310 GHz are fabricated and tested.**

I. INTRODUCTION

Computer-generated holograms are locally periodic diffraction gratings that modify both the reflected and transmitted electromagnetic fields. In conventional optical holograms, the grating structure is created by exposing a photographic film to the interference pattern of two separate, mutually coherent beams. An alternative method is to design the grating structure numerically and to print it or to etch it on the hologram material. These are called computer-generated holograms or diffractive elements.

Radio holograms are computer-generated holograms that operate with monochromatic radio waves. They are usually designed to perform a simple holographic function with high quality, such as forming a propagating plane wave from an incident Gaussian beam. Similarly, other beam forms, including radio-wave vortices and Bessel beams, can be formed with the use of appropriately fabricated radio holograms. Radio holograms find applications, in particular, in hologram-based compact antenna test ranges (CATR) [1].

II. AMPLITUDE AND PHASE HOLOGRAMS

We have investigated both amplitude and phase-type radio holograms. In amplitude holograms, the diffraction grating consists of metallic (copper) stripes on a dielectric film. In the millimetre-wave region, the skin depth of the radio field within copper is far less than one micron; hence, the metallic grating effectively reflects all radio-frequency field incident on the copper stripe and transmits the field through the slots between the stripes. Consequently, the transmitted field is modulated with a binary function corresponding to the hologram grating. The transmitted field is then diffracted according to the wavelength-scale structure caused by the hologram.

In phase-type holograms, the hologram structure features locally changing effective thickness seen by the electromagnetic wave; this is realized by varying the depth of the surface profile. The phase-type holograms consist of milled grooves on a dielectric substrate. The field passing through the grooves acquires a phase difference with respect to that between the grooves, leading to phase modulation of the transmitted field. Phase-type elements generally have higher diffraction efficiencies than their amplitude counterparts as their operation does not use partial blocking of the incident field.

III. DESIGN OF RADIO-WAVE HOLOGRAMS

The physical operation of a (thin) holographic grating is described with a transmission function, i.e. transmittance, $T(x,y)$, that relates the transmitted electromagnetic field to the incident field according to $E_u(x, y)=T(x, y)E_{in}(x, y)$. For nonamplifying hologram substrates, $T(x, y)$ is a complex function with $|T| \leq 1$.

A. Binary Quantization based on Scalar Theory

In simple cases, straightforward scalar theory may be sufficient for hologram design. There are several ways to discretize the desired transmission function in order to produce a binary-amplitude or binary-phase hologram. Here we describe two methods, one for each hologram type.

Amplitude hologram quantization. The transmittance is a complex-valued function $T(x, y) = a(x, y)\exp[i\psi(x, y)]$, where a is the amplitude modulation and ψ is the phase modulation. For amplitude holograms, it must be replaced with a real and positive quantity since amplitude elements do not allow modulation of the spatial phase of the field. A choice for the amplitude transmittance $T_A(x, y)$ may be expressed as [2]

$$T_A(x, y) = 0.5\{1+a(x, y)\cos[\Psi(x, y)]\}, \qquad (1)$$

where x, y are the coordinates in the plane of the hologram. Here, the phase is $\Psi(x, y) = \psi(x, y) + 2\pi\nu x$, where ν denotes the spatial carrier frequency that separates the diffraction orders produced by the hologram [3]. For a nonzero ν, the field leaves the hologram at an angle

$$\theta = \arcsin(\nu\lambda), \tag{2}$$

where λ is the wavelength of the electromagnetic field. Typically, we have designed the holograms to transmit the beam to an angle of 33° in order to create a so-called quiet-zone where the unwanted diffraction orders do not disturb the radio beam desired.

The transmittance of the corresponding binary amplitude hologram is given by [2, 4]

$$T_B(x, y) = 0,\ 0 \le 0.5[1 + \cos \Psi(x, y)] \le b$$

$$T_B(x, y) = 1,\ b \le 0.5[1 + \cos \Psi(x, y)] \le 1, \tag{3}$$

where

$$b = 1 - \pi^{-1} \arcsin a(x, y). \tag{4}$$

Ideally, a binary amplitude hologram either allows the incident field to pass through undisturbed (transmittance = 1) or blocks it completely (transmittance = 0).

Phase hologram quantization. In the case of phase holograms, the transmission function takes the form $T(x, y) = \exp[i\psi(x,y)]$, i.e., there is no direct amplitude modulation. The phase may also contain a linear carrier term if the hologram is to operate off-axis. The phase shift $\psi(x, y)$ is realized by directly modulating the depth of the surface profile $h(x, y)$. If the hologram substrate has a refractive index of n and the field exits to air, a binary phase-hologram structure is obtained, e.g., as follows:

$$h(x, y) = h,\ 0 \le \psi(x, y) < \pi$$

$$h(x, y) = 0,\ \pi \le \psi(x, y) \le 2\pi, \tag{5}$$

where the groove depth $h = \lambda/[2(n-1)]$ corresponds to a phase delay of π radians.

B. Parametrized Design of CATR Holograms

If the transmittance desired is modified with a suitably parametrized weighing function $W(x, y)$, the parameter values yielding a proper transmitted field may be found iteratively, provided that it is possible to rigorously compute the field produced by the hologram.

First, an initial weighing function is selected and the hologram is generated. The field near and within the hologram is calculated using the FDTD method (Finite Difference Time Domain, see Ref. [5]), and the quiet-zone field is then obtained with the use of physical optics. If the quiet-zone field does not meet the requirements, the weighing function is modified and a new hologram is synthesized and simulated. This process is repeated until a satisfactory result is achieved.

To make the computational effort tolerable, the hologram is assumed infinite and invariant along y in the FDTD modeling. This is a good approximation due to the gentle curvature of the slots and stripes in the y direction. This method is well-suited especially for designing CATR-type holograms that are used to form plane waves from incident Gaussian beams.

C. Back-propagation and Local Rigorous Optimization

If the holographic action of the grating is too complicated to allow a simple parametrization, the hologram can be designed by considering local structures. In this scheme, the required aperture field behind the hologram is found by numerically back-propagating the desired field onto the hologram.

In the back-propagation method, the beam profile is specified in the so-called signal window; for instance, in a plane 50 cm behind the hologram. The field is back-propagated to the hologram with the use of the angular spectrum representation [6]; the Fast Fourier Transform (FFT) algorithm can be efficiently utilized in the numerical implementation. Subsequently, the required transmission function can be calculated and local rigorous modeling of the grating is used to find a suitable hologram structure.

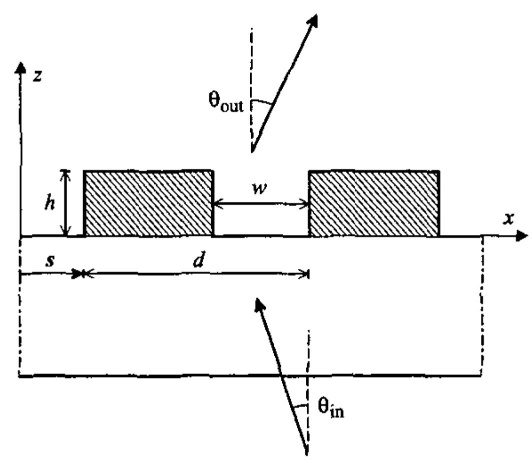

Fig. 1. Grating geometry and parameters for local rigorous optimization. The groove depth h and width w are to be optimized to obtain a proper transmission amplitude.

If the spacing of the stripes or grooves on the hologram is on the order of the wavelength, straightforward use of scalar theory is insufficient; rather, the rigorous electromagnetic theory must be applied [7]. In local rigorous optimization, it is assumed that the complex transmittance $T(x, y)$ has a constant spatial frequency in the vicinity of each location on the hologram. In the design process, the required values of the amplitude and phase modulations, $a(x, y)$ and $\psi(x, y)$, as well as the local grating period $d(x, y)$ and the angle of incidence θ_{in} are computed in every point of the hologram. Then, the optimal combination (w, h) with the desired amplitude a_r is determined, see Fig. 1. The local phase error is corrected according to the detour-phase principle [8].

IV. Experimental Results

Several holograms have been designed and fabricated, employing both the amplitude- and phase-hologram techniques. Elementary binary quantization and back-propagation were used in the design process of the amplitude holograms presented here. The phase-type beam splitter was optimized using the rigorous theory of diffraction gratings [7, 9].

The holograms are measured in the Radio Laboratory using AB Millimetre MVNA-8-350 network analyser with ESA-1 and ESA-2 extensions. A corrugated horn antenna is used as the transmitting antenna and the receiving antenna is a pyramidal horn antenna. A planar scanner is employed. All holograms measured in this work operate at 310 GHz.

A. Electromagnetic Vortices

We have produced an electromagnetic vortex with the use of an amplitude hologram. Figure 2 shows the field distribution and the phase of a singly charged vortex. The field is tapered to form a disc of diameter 20 cm, where the amplitude of the field is nearly constant. The phase of the vortex is designed to rotate around a loop by 2π, hence resulting in unit topological charge. The field amplitude necessarily vanishes along the vortex axis to preserve continuity.

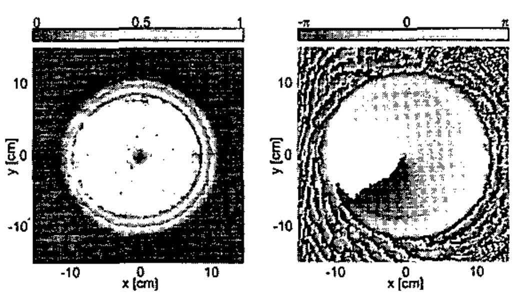

Fig. 2. Radio-wave vortex measured at a distance of 16 cm from the hologram. Field distribution (lhs), phase of the field (rhs).

B. Bessel Beams

We have also investigated amplitude holograms that form radio-wave Bessel beams [10]. Figure 3 shows the zeroth-order beam and its Fourier transform. Within a Bessel beam, the field energy is focused along the axis where the focal line of the beam has a radius on the order of one wavelength and it propagates without diffractive spreading. The central maximum is surrounded by several Bessel fringes with decreasing intensity for increasing distance from the beam axis. The field energy is directed onto the axis at the cone angle θ, hence the Fourier transform of the field forms a ring with a radius $\alpha = (\omega/c) \sin\theta$.

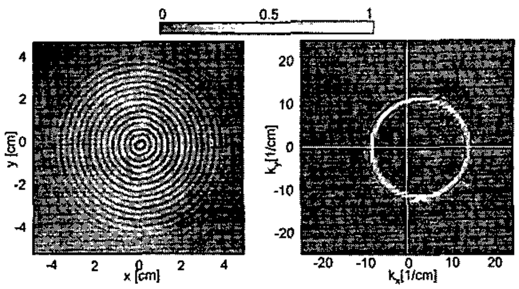

Fig. 3. Bessel beam measurement results. Zeroth-order Bessel beam $J_0(\alpha r)$ (lhs) and its spatial Fourier transform (angular spectrum) (rhs).

C. Back-propagated Fields

The radio field seen in Fig. 4 is formed with an amplitude hologram designed using the back-propagation technique. The hologram function is too complicated to be designed employing parametrization methods. The local rigorous optimization is to be used in future improvements of the field quality.

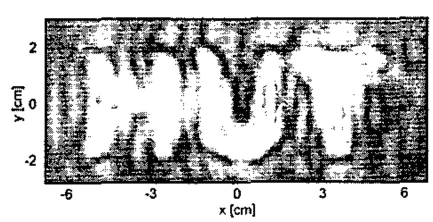

Fig. 4. Radio wave field shaped in the form "HUT" (Helsinki University of Technology). The hologram was designed using the back-propagation technique.

D. Phase Holograms

A beam-splitter phase hologram was fabricated and measured in order to test the dielectric material (Obomodulan®) and the fabrication method. In Fig. 5, the measured output, corrected with the computational directional pattern of the receiving open-ended waveguide, is shown. The designed effect of the hologram is to redirect the incident plane wave into seven beams of equal intensity. Due to the square aperture of the element, the beams unavoidably suffer from edge diffraction.

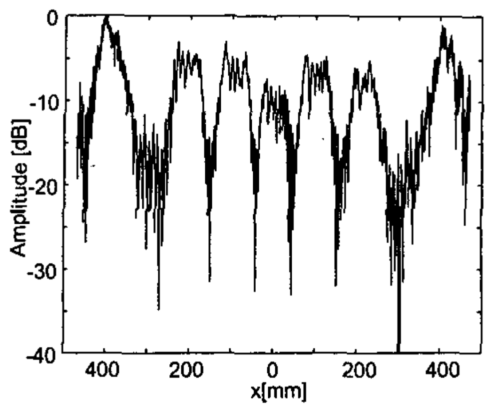

Fig. 5. Measured phase-element beam-splitter data, corrected with the computational directional pattern of the receiving waveguide.

V. Conclusions

We have designed and fabricated both amplitude-type and phase-type holograms for submillimetre-wave frequencies. The primary application area of these techniques is in the compact antenna test range (CATR) for testing satellite antennas. We have also, for the first time, synthesized computer-generated holograms to produce Bessel beams and a radio-wave vortex at submm-wave frequencies.

In addition to the binary quantization schemes applied in this work, several other coding schemes of phase and amplitude have been suggested in the optical regime, utilising subwavelength grating structures [3]. Such feature sizes are difficult to fabricate at optical wavelengths but they may in fact be readily realized in the radio-wave regime. Thus, the existence of a large variety of hologram techniques holds a significant promise for the hologram research and radio-wave applications in the future.

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