Millimeter-Wave Beam Shaping Using Holograms

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***Abstract*—We synthesize amplitude- and phase-type computer-generated holograms (diffractive gratings) for shaping millimeter-wave fields. We design holograms using quasi-optical back-propagation and rigorous optimization methods adopted from diffractive optics. We present experimental results from a plane-wave-generating hologram and a custom-designed field shaper at 310 GHz. Holograms can be applied, e.g., in a compact antenna test range and we propose their use for alignment purposes.**

***Index Terms*—Beam steering, diffraction, holographic gratings, millimeter-wave technology, propagation, submillimeter-wave technology.**

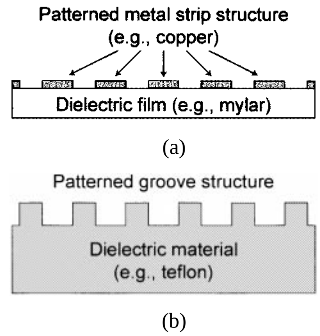

Fig. 1. Local grating structure of: (a) an amplitude and (b) a phase hologram.

I. Introduction

COMPUTER-GENERATED holograms are locally periodic diffraction gratings that modify both the reflected and transmitted electromagnetic fields. In conventional optical holograms, the hologram structure is created by exposing a photographic film to the interference pattern of two separate mutually coherent beams, one scattered from the object and the other constituting a reference plane-wave beam. Analogous techniques are applied in, e.g., electron holography [1] and digital holography [2]. An alternative method is to design the hologram structure numerically and to print it or to etch it on the hologram substrate material; these are called computer-generated holograms (CGHs), i.e., diffractive elements. The latter approach is used in the fabrication of high-quality optical instruments such as diffractive lenses and beam splitters [3].

Radio holograms are CGHs that operate with monochromatic radio waves. They are usually designed to perform a simple function with high quality, such as forming a propagating plane wave from an incident Gaussian beam. Similarly, as we have shown in [4]–[6], other beam forms, including radio-wave vortices and Bessel beams, can also be formed with the use of appropriately synthesized radio holograms. In this paper, we describe how more complex profiles can be designed, for instance, using the back-propagation method. Thus far, radio holograms have found their most useful applications in hologram-based compact antenna test ranges (CATRs) at millimeter waves [7]; the development work continues, however, aiming for satellite antenna testing at submillimeter waves.

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II. Amplitude and Phase Holograms

We have investigated both amplitude- and phase-type radio holograms. In the amplitude holograms, the diffraction grating consists of metal strips on a dielectric film [see Fig. 1(a)]. We have used Mylar films (75-μm thick, relative permittivity $\varepsilon_r = 3.3$) with a copper layer (17 μm) atop it. The desired pattern is fabricated using photolithography and chemical wet etching. In the millimeter-wave region, the skin depth of the radio-wave field within copper is far below 1 μm; hence, the metallic grating effectively reflects all the RF field incident on the copper strip and transmits the field through the slots between the strips. Ideally, 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 structured pattern comprising the hologram. However, in reality, the modulation of amplitude is never purely binary. The deviation from the ideal binary form is especially pronounced in the case of wavelength-scale diffractive structures, and further optimization is, therefore, necessary by rigorous modeling methods [8]. Typically, the first diffraction order generated by the hologram is utilized. Such an amplitude hologram can also indirectly modulate the phase of the first-order field, as the phase can be coded in the positions of the copper strips.

In phase-type holograms, the hologram structure features a locally changing effective thickness encountered by the electromagnetic wave. In our study, the phase-type holograms are realized with milled grooves on a dielectric substrate [see Fig. 1(b)]. The field passing through the grooves acquires a phase difference with respect to that between the grooves, leading to a phase modulation of the transmitted field. Generally, phase-type elements feature higher diffraction efficiencies than their amplitude counterparts since their operation does not involve partial blocking of the incident field.

III. Design of Millimeter-Wave Holograms

The physical operation of a (thin) holographic grating is described with a transmission function, i.e., transmittance $T(x,y)$, which relates the transmitted electromagnetic field $E_{\rm tr}$ to the incident field $E_{\rm in}$ according to

$$E_{\rm tr}(x,y) = T(x,y)E_{\rm in}(x,y). \quad (1)$$

The transmittance can be expressed as $T(x,y) = A(x,y)\exp[i\Psi(x,y)]$, where A is the amplitude modulation, Ψ is the phase modulation, and (x,y) are the coordinates in the plane of the hologram.

The goal in the design process is to find such a transmittance and the corresponding hologram structure that produces a wave with the field distribution described by a specified complex function

$$F(x',y') = a(x',y')\exp\left[i\psi(x',y')\right]$$

where a and ψ refer to the amplitude and phase in the beam-coordinate system (x',y'). Here, the beam-coordinate system may be different from the hologram-coordinate system. In the scalar-theoretical treatment, the hologram structure is directly related to the desired transmittance, but in the case where electromagnetic theory is required, sophisticated optimization methods are required to obtain the hologram structure.

The hologram can operate on-axis, i.e., a normally incident input field is converted into a goal field around the z-axis, in which case, the desired transmittance $T(x,y)$ reduces to $F(x,y)$. However, on-axis operation limits the degrees of freedom in the design process and the achievable waveforms; in particular, amplitude holograms can only produce direct amplitude modulation, but no phase modulation.

Full control of the phase and amplitude can be attained if the hologram is designed to operate off axis by adding a spatial carrier frequency to the goal field and utilizing a nonzero diffraction order, typically the first diffraction order, of the resulting diffraction grating structure to produce the field F. Assuming carrier periodicity in the x-direction, the transmittance amplitude and phase are now

$$A(x,y) = a(x',y') \quad (2)$$

$$\Psi(x,y) = \psi(x',y') + 2\pi\nu x \quad (3)$$

where ν is the carrier frequency, and (x,y) and (x',y') are related by a simple rotation of the coordinate system around the y-axis. Typically, for a hologram operating at the first diffraction order, the maximal transmittances are $|T| = 1/\pi$ for amplitude holograms and $|T| = 2/\pi$ for phase holograms, both according to scalar theory.

For a nonzero ν, the first diffraction order is emitted from the hologram at the angle

$$\theta = \arcsin(\nu\lambda) \quad (4)$$

where λ is the wavelength of the electromagnetic field. In our study, the holograms are typically designed to transmit the beam to the angle 33° in order to create a volume where the unwanted diffraction orders do not disturb the custom-designed radio beam.

In Sections III-A–C, we first describe elementary schemes for determining and quantizing the transmittances for amplitude and phase holograms and then consider the two design algorithms for obtaining the corresponding hologram structure by rigorous electromagnetic theory and for calculating the required transmittance on the plane of the hologram.

A. Binary Quantization Based on Scalar Theory

Straightforward scalar theory may sometimes 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.

1) Quantization of Amplitude Holograms: For amplitude holograms, $T(x,y)$ is a real positive function since amplitude elements do not enable a modulation of the spatial phase of the field. Ideally, a binary amplitude hologram either allows the incident field to pass through undisturbed (transmittance = 1) or blocks it totally (transmittance = 0). Hence, the complex function T has to be converted to a binary real function T_B. One formulation of a suitable binary transmittance corresponding to the desired goal field is [9], [10]

$$T_B(x,y) = 0, \quad 0 \le \frac{1}{2}\left[1+\cos\Psi(x,y)\right] \le b \quad (5)$$

$$T_B(x,y) = 1, \quad b \le \frac{1}{2}\left[1+\cos\Psi(x,y)\right] \le 1 \quad (6)$$

where

$$b = 1 - \frac{1}{\pi}\arcsin a(x,y) \quad (7)$$

and $\Psi(x,y)$ is defined by (3).

2) Quantization of Phase Holograms: For phase holograms, the transmittance assumes the form $T(x,y) = \exp[i\,\Psi(x,y)]$, i.e., there is no direct amplitude modulation. The phase shift 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 producing a phase-only goal field is obtained, e.g., as follows:

$$h(x,y) = h, \qquad 0 \le \Psi(x,y) < \pi \quad (8)$$

$$h(x,y) = 0, \qquad \pi \le \Psi(x,y) \le 2\pi \quad (9)$$

where the groove depth $h = \lambda/[2(n-1)]$ corresponds to a phase delay of π rad. Amplitude modulation can be realized by modulating the groove depth of the profile.

B. Local Rigorous Optimization

If the spacing of the strips or grooves on the hologram is on the order of a wavelength, straightforward use of scalar theory proves insufficient; rather, rigorous electromagnetic theory must be applied [8]. When the strip spacing on the hologram remains constant within the range of several adjacent strips, the structure may be assumed locally periodic without making a significant error. Hence, methods developed for diffraction gratings can be applied to analyze and optimize these structures.

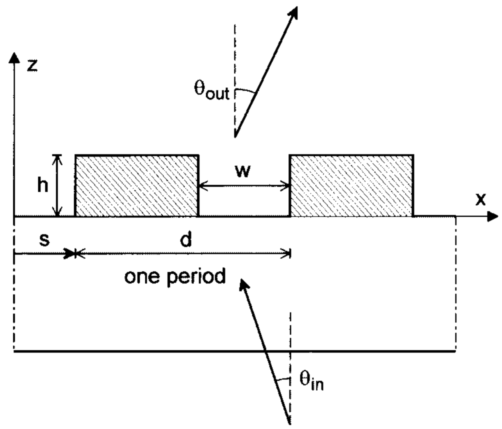


Fig. 2. Grating geometry and parameters for local rigorous optimization. For phase holograms, the groove width w and depth h on the dielectric substrate are to be optimized to obtain a proper transmission amplitude. For amplitude holograms, only the groove width w is optimized since the thickness h of the metallization on the dielectric film is fixed. The entire grating is shifted by the vector $\mathbf{s}$ to correct for local phase deviations.

In local rigorous optimization, the complex transmittance $T(x, y)$ is assumed to have a constant spatial frequency in the vicinity of each location on the hologram and the structure of the period to remain invariant. 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 $\theta_{\text{in}}(x, y)$ are computed at every point of the hologram. The optimal structure within one period is then determined to yield the desired amplitude transmittance a_r (see Fig. 2). The local phase error is then corrected using the detour-phase principle [11].

C. Back-Propagation Technique

To use the quantization schemes described above, the field profile on the hologram surface must be known. If a certain profile is desired at a finite distance from the hologram, the field profile at the hologram, necessary to produce the desired field, must be determined. For this, the back-propagation technique can be used. Since local rigorous optimization does not take into account the overall operation of the hologram, the back-propagation method can also be used to ascertain that there occur no defects in the field profile at a given distance. For instance, diffraction from the finite aperture of a hologram element causes deterioration of the beam fidelity upon propagation and must be handled separately. In this scheme, the required aperture field behind the hologram is found by numerically back-propagating the desired field onto the hologram. Hence, unwanted diffractive deterioration of the beam can be eliminated at the specified distance.

In the back-propagation method, the beam profile is specified within the signal window, in a plane perpendicular to the propagation axis; e.g., in a plane 50 cm behind the hologram. Fig. 3 illustrates the design process. The field is back-propagated onto the hologram with the use of the angular-spectrum representation [12]; the fast Fourier transform (FFT) algorithm can be efficiently utilized in the numerical implementation. Subsequently, the required transmission function can be calculated and either the scalar theory or local rigorous modeling may be used to find a suitable hologram structure to convert the incident field into the output field.

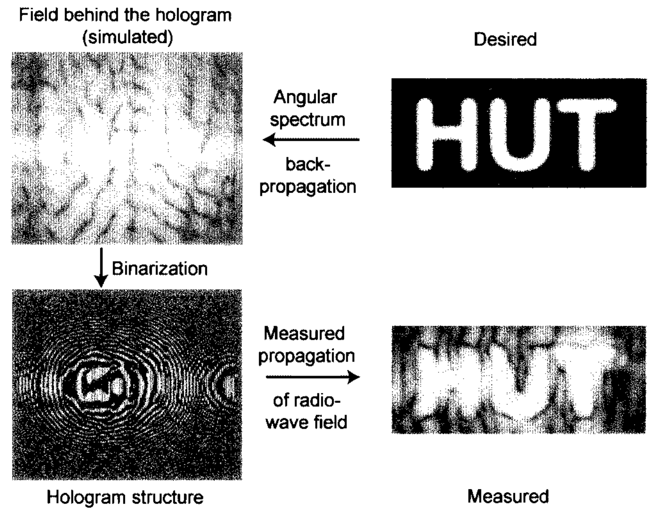


Fig. 3. Back-propagation technique. Fourier transform of the *desired* field profile at a certain distance from the hologram is propagated onto the hologram to determine the field amplitude behind the hologram. The required hologram structure is then calculated. Finally, the actual *measured* field distribution is obtained experimentally [13], [14].

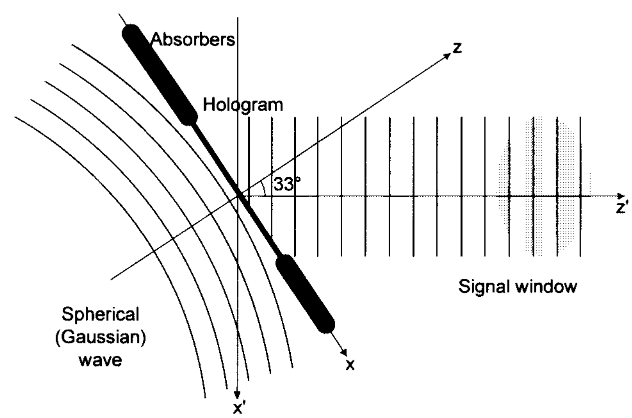


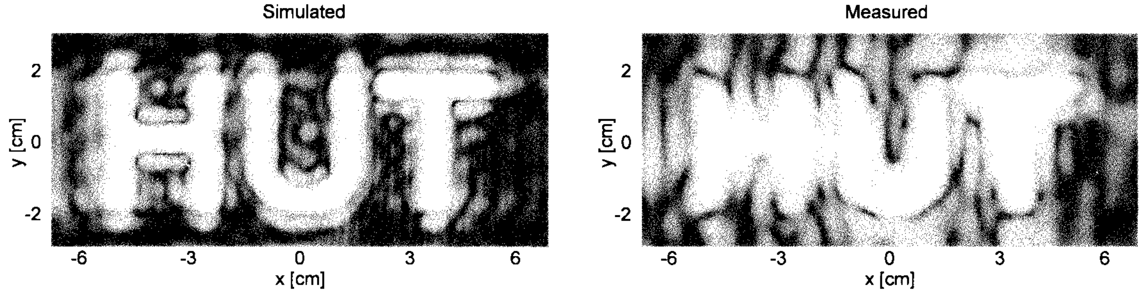
Fig. 4. Schematic of the measurement geometry for the holograms. The field profile is measured in the signal window. The measurement plane is normal to the z'-axis. Absorbers are used around the hologram and the whole setup in order to avoid direct and reflected radiation in the signal window.

IV. Experimental Results

We have designed and fabricated several holograms, employing both the amplitude- and phase-hologram techniques. All the hologram results presented here have been designed using the back-propagation scheme; both scalar theory and rigorous optimization are used. Previously, we have presented results obtained using elementary binary quantization based on scalar theory [4]–[6].

A. Measurement Setup

The holograms are measured using an AB Millimètre MVNA-8-350 network analyzer with ESA-1 and ESA-2 extensions. A corrugated horn antenna is used as the transmitting antenna and a pyramidal horn antenna is the receiving antenna. A planar scanner is employed to obtain the two-dimensional



(a) (b)

Fig. 5. Radio-wave field shaped in the form "HUT." (a) Simulated and (b) measured field profile. The hologram was designed using the back-propagation technique.

field profile in the signal window. A schematic view of the measurement geometry is shown in Fig. 4. Absorbers are used around the hologram and the whole setup to block the wave propagating straight from the transmitter to the receiver and to minimize reflections. The desired beam is designed to propagate into an angle of 33° to avoid interference with the waves propagated rectilinearly through the hologram. All holograms measured in this work operate at 310 GHz.

B. Custom-Designed Field Patterns

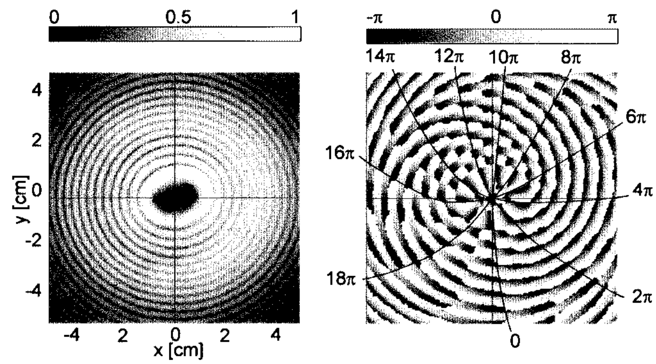
The back-propagation method facilitates the synthesis of holograms that serve to produce complicated field patterns in the desired signal window. Using the design scheme illustrated in Fig. 3, we have fabricated a hologram that yields a field pattern of the form "HUT" (acronym for the Helsinki University of Technology); the measured field in the signal window (1 m from the hologram center) is illustrated in Fig. 5. Due to the binarization of the hologram structure, the theoretical (simulated) field also differs from the desired one. However, the measured and simulated fields are mutually in fair agreement.

The physical operation of custom-designed holograms is, in general, complicated. Hence, we have chosen to use the back-propagation method together with local design of the hologram. At present, the hologram itself is synthesized using the elementary binarization described in Section III-A. In order to further improve the fidelity of the field, local rigorous optimization of the hologram is to be performed.

C. Field Profiles Designed Without Back-Propagation

To exemplify a field profile produced without the use of the back-propagation technique, we present Bessel-beam and radio-wave vortex measurements. Previous results of these field shapes have been reported in [4]–[6]. In Fig. 6, the field amplitude and phase of a tenth-order Bessel beam are shown. The central minimum of the beam is due to the vorticity of topological charge 10 carried by the beam.

Fig. 7 illustrates the deterioration of the field profile upon propagation in the case of an electromagnetic vortex. An electromagnetic vortex, analogously to an optical one, has the phase of the field rotating through $2\pi N$ around any loop encircling the vortex axis; the integer N is the topological charge (vorticity) of the vortex. The field profile is a disk with a zero in the middle to preserve continuity. Near the plane of the hologram,



(a) (b)

Fig. 6. Tenth-order Bessel-beam measurements. (a) Field amplitude and (b) phase of the field.

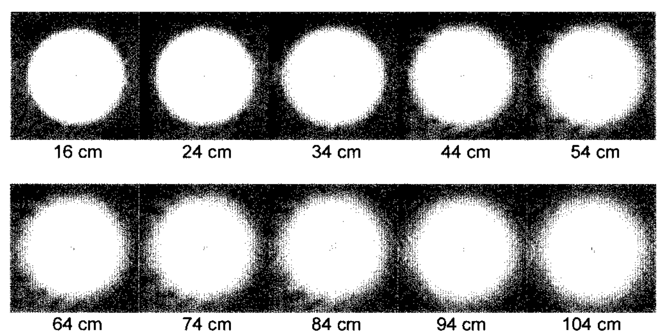


Fig. 7. Deformation of the electromagnetic vortex field profile upon propagation. The measurement distance from the plane of the hologram is given below each field profile. The area of each picture is 10×10 cm^2.

the field amplitude is constant. As the distance from the hologram increases, diffraction rings appear due to the circular aperture. Using the back-propagation method, the effect of the aperture diffraction on the field profile can be removed at a certain distance. As seen in Fig. 7, the node in the center of the vortex core propagates invariantly without deformation. This property of the vortex field may be utilized for alignment purposes, analogously with the applications of optical vortices. In optics, corresponding waveforms have also been used, for example, as phase markers and for particle trapping [15]–[17].

D. Phase Holograms Producing Plane Waves

To test the design and fabrication methods for phase holograms, as well as the fabrication materials, we have chosen to synthesize phase holograms for plane-wave generation.

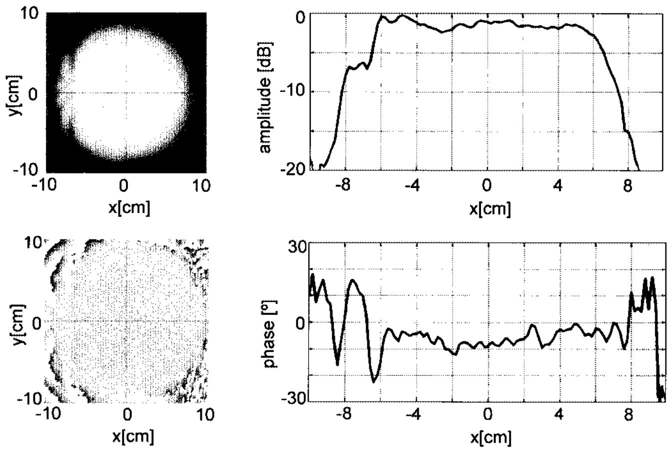


Fig. 8. Measurements of a plane wave generated using a phase hologram. Distributions of (above) amplitude and (below) phase of the wave.

To this end, we have used the back-propagation approach with local rigorous optimization to design a phase hologram generating a uniform planar field with a diameter of 10 cm at the 1-m distance from the hologram. The hologram structure of size 28 cm $\times$ 24 cm was fabricated on a Teflon substrate by a computer-controlled milling machine. Fig. 8 shows the measured amplitude and phase distributions in the goal plane. Excluding the amplitude peak on the left edge, the amplitude and phase variations within the signal window are approximately 2 dB and 10°, respectively.

V. Conclusions

We have designed and fabricated both amplitude- and phase-type holograms operating at submillimeter-wave frequencies. The primary application area of these techniques has been in the CATR for testing satellite antennas. We have also synthesized CGHs to produce Bessel beams, radio-wave vortices, and custom-designed field profiles at 310 GHz.

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

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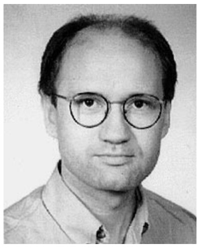

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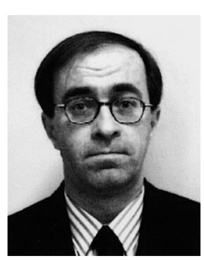

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