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RECORDING AND REPRODUCTION OF MICROWAVE HOLOGRAMS USING A SCANNING PROCEDURE AND THEIR SUBSEQUENT OPTICAL PROCESSING

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16. Abstract

A microcomputer controlled measurement set-up is introduced that allows the recording of intensity distributions in microwave fields and their visual reproduction by quasi-rotationally symmetrical scanning. The methods chosen for information processing are deduced from diffraction- and system theory. The applications described comprise diagnostics of aperture distributions and the determination of resulting far-field patterns of arrays of antennas.

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RECORDING AND REPRODUCTION OF MICROWAVE HOLOGRAMS USING A SCANNING PROCEDURE AND THEIR SUBSEQUENT OPTICAL PROCESSING

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1. Introduction

Intensity distributions in non-optical wavefields have been /51
made visible for some time and have been stored on photo-sensitive material [1]. Holographic techniques also provide the opportunity to freeze-in the complex amplitude of a stationary field at any point and to reproduce it in the optical range [2, 3].

Of course there is no medium for microwaves comparable to photographic material, but liquid crystals and polaroid films can be used for such purposes via temperature effects [4, 5]. Compared to this method, the scanning methods where the field is scanned point-by-point or line-by-line with one or more probes, offers advantages of relatively small transmission power with free selection of the wavelength and the potential for measured-value processing before its transferral [6, 7]. If computers are used to control the probe and for storage of measured data, reproductions can be performed as often as desired to enhance picture quality, or a wholly numerical process can be used. Therefore, a computer-based scanning method was selected for the recording and reproduction of microwave holograms.

2. The Computer-Based Measurement Center

The recording framework (fig. 1) operating by the scanning principle is made of plastic--as much as possible--and permits a 3-dimensional positioning of the probe on the lines of a cylindrical coordinate system. This permits the probe to be moved efficiently over the sphere surface [8]. Five-phase stepping motors provide the drive power to shift the probe in the R, Θ and z-directions; these motors have the advantage of eliminating in

*Numbers in the margin refer to pagination in the original text.

principle, a report on the position of the probe. Since the probe is moved quasi-continually in a circular direction, an angle-encoder is used to provide a positioning control. By means of a mechanical system, the probe orientation in space is held constant during its circular motion.

The maximum diameter of the scanned surface amounts to 800 mm, the path resolution in the r-direction is 3 micrometers, in the θ-direction, 10^{-4}. /52

Fig. 1: Recording Frame and Scanning Electronics

The electronics needed for the stepping motors and angle encoder are placed in a 19" housing.

An open hollow waveguide with outlet-connected crystal detector for a range of 26.5 to 40 GHz (fig. 2) isused as measuring probe; it sends its values via a DC-amplifier to the controlling computer. At an S/N-ratio of 60 dB, the minimum detectable power is about 15 nW.

Fig. 2: Hollow Waveguide Probe

The block diagram (fig. 3) shows the interaction of recording frame, scanning electronics and computer. The used microcomputer has an 8-bit architecture; it also has an expandable memory of 64 kbytes RAM and 4 disc drives with a total of 2 megabyte capacity. In 30 minutes, about 300,000 position and intensity values can be recorded and stored.

Figure 4 shows the reproduction frame which represents the smaller pendant to the recording frame and is also controlled by the computer. Instead of the probe, a semiconductor light source

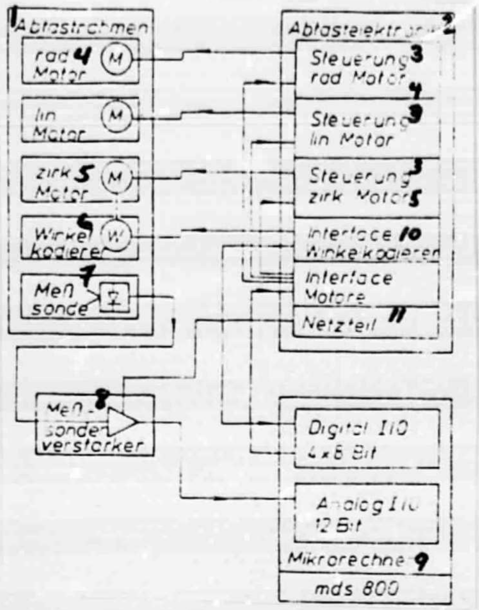

Fig. 3: Block Diagram of the Scanning System for Recording Operation

Key: 1-scanning frame 2-scanning electronics 3-control 4-radial motor 5-circular motor 6-angle encoder 7-probe 8-probe amplifier 9-microcomputer 10-interface, angle encoder 11-mains section

Fig. 4: Reproduction Frame

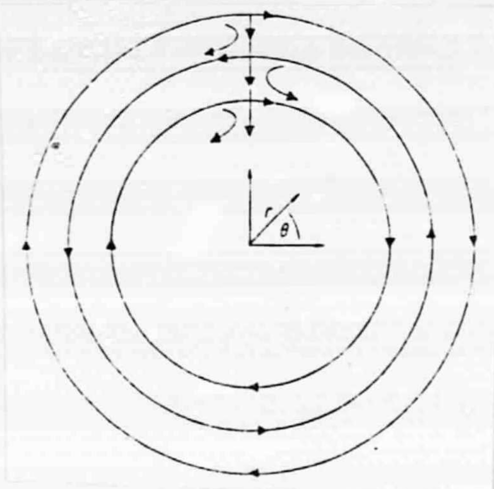

Fig. 5: Probe LED Path

is accurately positioned here, and its brightness is pulse-modulated. The motion path chosen for the probe and LED is shown in fig. 5; the alternating clockwise and counter-clockwise operation with interim variation of the radial position from outside to inside is indicated in the figure.

The image produced on picture film as a darkened distribution of the intensity present during the photograph, is reduced in a final step (photographically) to a diameter of about 5mm. Figure 6 shows a typical set-up of the subsequent, optical information

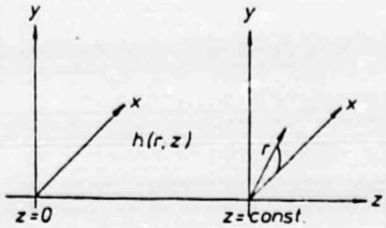

Fig. 7: System of Parallel Planes

Fig. 6: Optical Computer

processing. This part of the entire process of production and processing of microwave holograms is explained in more detail below.

3. Optical Information Processing

It is appropriate to describe the recording of microwave holograms and their reconstruction in the optical range with the propagation of waves between planes. Such a procedure will be sufficient for linear polarization of the illuminating waves, and by neglecting depolarizing effects on objects of the scalar, homogeneous Helmholtz equation. Thus, if we consider the propagation of waves of wavelength λ between two planes separated by distance z in free space (fig. 7), then the response of this linear, rotation-symmetric system to any input stimuli, is known to be a convolution of input function and pulse response:

$$u\big|_{z=const.} = u\big|_{z=0} ** h$$

We thus obtain a system-theoretical formulation of the Rayleigh-Sommerfeld diffraction integral, from which the exact pulse response can then be found:

$$h(r;z) = \frac{z}{2\pi} \frac{e^{+j\frac{2\pi}{\lambda}\sqrt{r^2+z^2}}}{r^2+z^2} \left(-j\frac{2\pi}{\lambda} + \frac{1}{\sqrt{r^2+z^2}}\right)$$

The usual approximation of the integrand for large spacing z, measured in wavelengths, and for near-axis or linear approximation of the amplitude and square of the phase, leads to the Fresnel approximation of the pulse response:

$$h_{Fr} = \frac{1}{j\lambda z} e^{j\frac{2\pi}{\lambda} z} e^{j\frac{2\pi}{\lambda}\frac{r^2}{2z}} \quad ; \quad z \gg \lambda, \quad z \gg r_{max}$$

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If we simplify and write [9, 10]:

$$q(r; \frac{1}{\lambda z}) = e^{j\frac{2\pi}{\lambda}\frac{r^2}{2z}} \quad \text{with} \quad q\,q^* = 1$$

then the Fresnel diffraction integral can be represented as follows (neglecting the non-convolution-relevant factor):

$u|_{z=const.} = u|_{z=0} ** q = q \cdot \mathcal{F}\{u|_{z=0} \cdot q\}$ $|_{RFK \rightarrow RK}$ where we have:
$\mathcal{F}$: 2-dimensional Fourier transformation, RFK: Space frequency coordinates and RK: Space coordinates.

By using the properties of q, from the convolution there results a Fourier transformation of the q-loaded input function, the Fresnel transformation of u along the distance z, with a suitable imaging of the space-frequency coordinates onto space coordinates. If the field distribution near the axis in a plane z is large compared to λ, then we arrive at the [word missing] in the initial plane through a Fresnel retransformation, i.e. through a Fourier retransformation applied to the distribution in the Fresnel field affected by the conjugated-complex phase factor: /54

$$u|_{z=0} = \mathcal{F}^{-1}\{u|_{z=const.} \cdot q^*\} \cdot q^* \quad .$$

If the spacing z is large compared to the ratio of the surface area of an aperture in the initial plane to the used wavelength, then the phase factor in the integral dependent on the aperture coordinates, is nearly equal to one and we obtain the Fraunhofer diffraction integral which produces a Fourier transformation relation between the distribution in an aperture and its far-field:

$u|_{z=const.} = q \cdot \mathcal{F}\{u|_{z=0}\}$ $|_{RFK \rightarrow RK}$ for $z \gg (\text{aperture diameter}_{max})^2/\lambda$.

From measurements in the Fresnel field of an aperture antenna, conclusions can be drawn about the antenna availability and about the radiation pattern.

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The holography technique now permits the storage of such complex fields only on intensity-sensitive media by overlapping the desired object wave by a coherent reference wave. After generating an amplitude transmittance as linearly as possible through the available intensity distribution, in a second step the wave field of the object is reconstructed, generally by using a reproduction wave which resembles the reference wave during the recording.

The measuring set-up in step one delivers a hologram in the millimeter-wave range whose structure is stored in the computer, and in the 2nd step, a reduced image on photo material which is reconstructed with He-Ne-laser light of about 633 nm. The ratio of wavelengths is about 13,500; the hologram diminution factor attainable in practice, is 170.

Regarding the spherical lenses used in the next step one can say that they convert a spherical wave with midpoint g into one with midpoint b. For a lens with focal length f there follows by Fresnel approximation, its complex amplitude transmittance:

$$L = q^*(r; \frac{1}{\lambda f})$$

If observations are made in the rear focal plane of the lens, then it acts like a two-dimensional Fourier transformer for signals in the front focal plane (fig. 8), which provides the actual reason for optical processing of microwave holograms (besides the fact that lenses for the microwave range are complex and of poor quality).

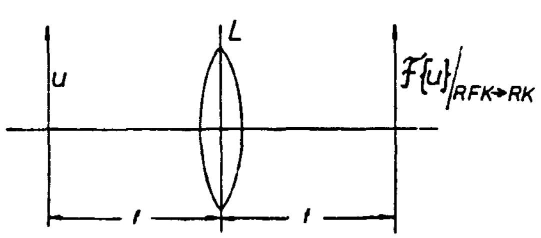

Fig. 8: Lens as Fourier Transformer

4. Applications /55

Figure 9 shows the recording set-up selected for the application examples.

The source of the spherical reference wave has the same distance from the hologram plane as the object; we obtain a so-called lensless Fourier hologram which is characterized by the interference terms appearing in the hologram plane which contain the spectral distribution of the aperture distribution affected with a quadratic phase factor.

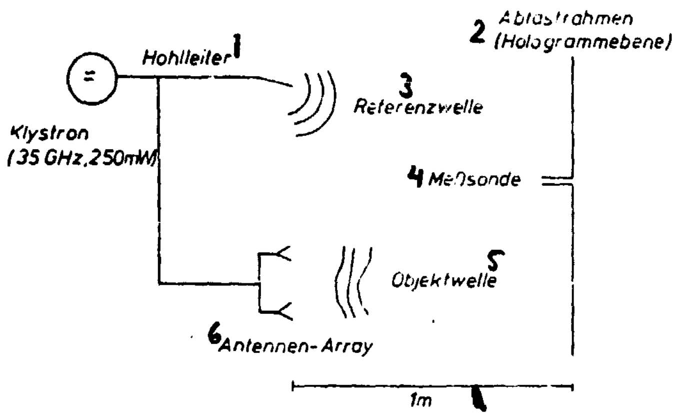

Fig. 9: Principle of the Recording Set-up

Key: 1-hollow waveguide 2-scanning frame (hologram plane) 3-reference wave 4-probe 5-object wave 6-antenna array

As a sample application of microwave holography, the localization of defective elements in antenna arrays was selected [11] (fig. 10). The photo shows the intact array of pairs of the same rectangular horns which are linked via magic T-pieces with symmetry-control outputs and which are powered in counterphase from an E-branching. Figure 11 shows the hologram taken with 236 scanning circles which has the typical interference structure. Figure 12 shows the optically reconstructed intensity distribution in the aperture plane and we see the 4 emitting elements and the clear size differences of the horn pairs. The far-field obtained through Fourier transformation and unfolding (by defocussing) for the antenna array is shown in fig. 13 together with the expected group characteristics.

Fig. 10: Antenna Array

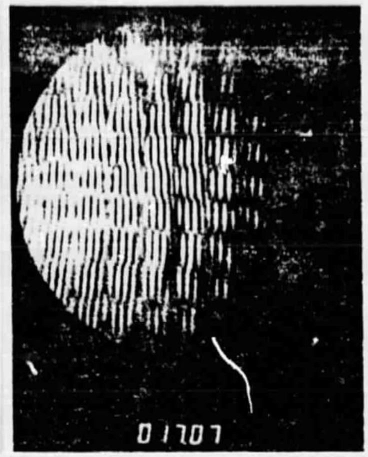

Fig. 11: Intact Array

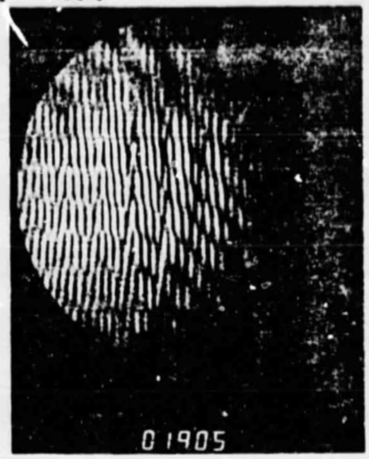

Fig. 14: Defective Array

Fourier holograms

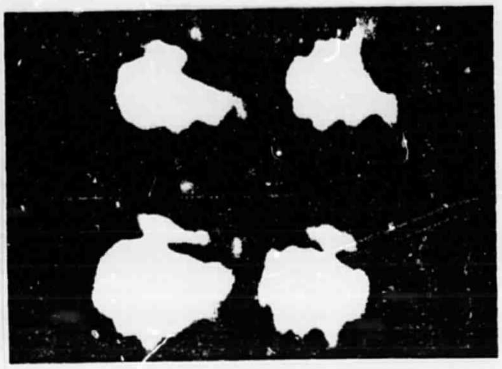

Fig. 12: Aperture dist. int. array

Fig. 13: Far-field, int. array

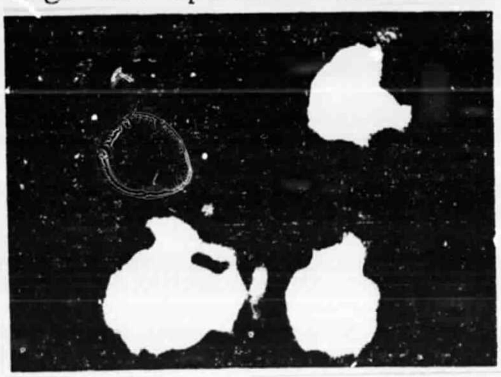

Fig. 15: Aperture dist. defective array

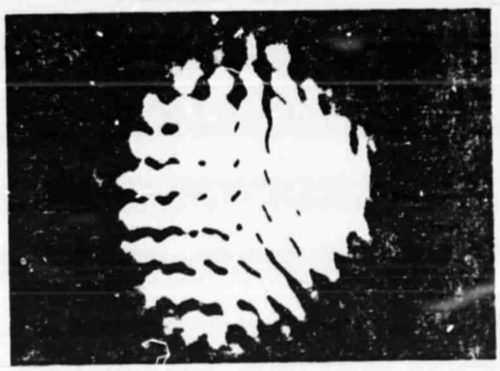

Fig. 16: Far-field, def. array

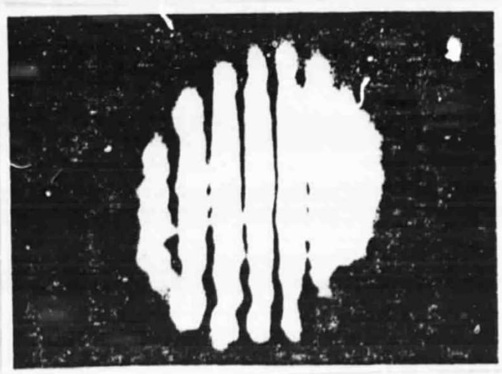

Fig. 17: Two elements in H-plane

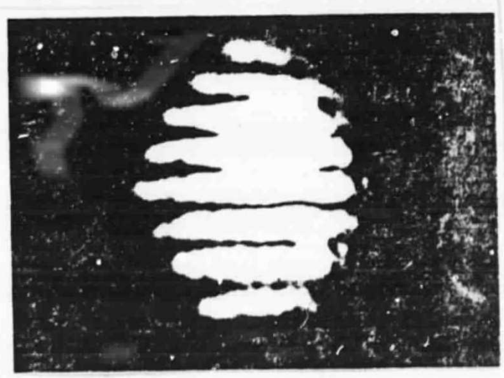

Fig. 18: Two elements in E-plane

Far fields

The array was then reduced by one emitting element through a reflection-free cover. The resulting hologram (fig. 14) shows no great changes compared to that of the intact array, but the reproduced aperture distribution shows the defect (fig. 15). The constructed far-field is also clearly deformed (fig. 16).

The potential of performing changes in the optical range on aperture distributions yields additional applications. For instance, the thinning out of (usually stochastic) antenna fields can be simulated. As an example for such an application, one element of the defective array was faded-out optically. We then obtain the far-field (fig. 17) of a double horn excited in phase in the H-plane, whose maximum was found photometrically on the antenna axis and the far field (fig. 18) of a double horn now excited in phase located in the E-plane with a minimum on the axis.

The potentials of the computer had not been fully utilized, for instance, only relatively rough measurements were performed to linearize the final amplitude transmittances. Figure 19 provides a hint about these potentials; it shows again the aperture distribution of the intact array, reconstructed from a non-linearized hologram and thus affected by diffraction patterns of higher order. The fields evaluated photometrically already indicate good agreement with theoretical or directly-measured values, especially for bundled antennae.

Additional applications are found in tracking anomalies in opaque dielectric substances, in the investigation of scattering fields--which could be done by turning the polarization directions of the reference wave and the probe by 90°, or vectorally--and in holographic interferometry.

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Fig. 19: Aperture Distribution
Intact Array (not linearized)

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