IMAGE PROCESSING IN MICROWAVE HOLOGRAPHY FOR DIELECTRIC OBJECTS

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Summary

An efficient imaging technique for scattering dielectric plane objects is presented which is based on microwave holographic methods. FRESNEL-KIRCHHOFF’s diffraction integral in its discrete form with a suitably extended object function provides an appropriate numerical hologram simulation by which the relevant imaging parameters may be systematically investigated. The image reconstruction is carried out digitally, where the FRESNEL approximation enables the use of standard FFT techniques. Comparison between simulated and measured holograms verifies the numerical simulation technique. The results of the numerical image reconstruction show that a reliable identification of the dielectric objects is possible. The efficiency of the signal processing method is demonstrated at the image reconstruction of a more complicated dielectric object (glass, with a permittivity of 8) shaped in form of the letters "RW" by utilizing a computer simulated hologram.

2. Theory

The computer simulation of the diffracted wave at the point $P_{11}$ in the hologram plane (Fig. 1) is calculated by FRESNEL-KIRCHHOFF’s diffraction integral in its discrete form.

Fig. 1 Object and hologram plane
The complex hologram function $U_{110}(z)$ is taken for $I$-$L$ points with the sample distance $\Delta x_0$, $\Delta y_0$.

$$U_{110}(z) = \frac{1}{2\pi} \sum_{\mu=1}^{P-1} \sum_{\nu=1}^{L-1} \int \frac{d^{2} \Phi_{\mu\nu}}{d \nu} \sum_{n=0}^{N-1} \sum_{m=0}^{M-1} e^{j k \Delta z_{\mu\nu}} e^{j \frac{k}{\lambda_{0}}} \frac{s_{mnp}}{s_{\nu}}
$$

with $\lambda_{0} = \frac{c}{f}$ - wavelength

$$k_{\mu\nu}^{2} = \frac{\lambda_{0}^{2}}{\lambda_{0}^{2} - \lambda_{\mu\nu}^{2}}$$

$\lambda_{\mu\nu}$ - field wavelength of the diffracting surfaces

$$s_{mnp} = \frac{\lambda_{0}^{2} \Delta x_{\mu\nu}^{2} \Delta y_{\mu\nu}^{2}}{2}$$

$$r_{\nu} = \frac{\lambda_{0}^{2} \Delta x_{\mu\nu}^{2} \Delta y_{\mu\nu}^{2}}{2}$$

$$\varphi_{\nu} = \frac{\rho_{\nu}}{\rho_{\nu} - D}$$

$$\cos(\varphi_{\nu}) = \frac{r_{\nu}^{2} + \rho_{\nu}^{2} - D_{\nu}^{2}}{2 \rho_{\nu} r_{\nu}}$$

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The general form of equation (1) includes the application of the multifrequency holography technique and is written for threedimensional objects, which can be subdivided in $P$ planes with the dimensions $\Delta x \times \Delta y \times N$. The subscript $q$ denotes the discrete frequency used. For the numerical examples (dielectric plates) with $P=1$ calculated in this paper, however, already the monofrequency holographic imaging technique provides sufficient resolution of the object shape.

The scattering characteristics of the plane dielectric object are included by the complex reflection coefficient $R_{mnq}$ which is based on the uniform geometrical theory of diffraction (UTD)\(^9\). The subscript $q$ denotes the frequency, and $mn$ is the number of the related rectangular object segment of size $\Delta x \times \Delta y$

$$R_{mnq} = \frac{r_{1} \cdot (1 - r_{2} \cdot r_{3})}{1 - r_{1}^{2} \cdot r_{2} \cdot r_{3}}$$

The coefficients in (2) are given by

$$r_{1} = \frac{\cos \varphi - j e_{rmn} \sin^{2} \varphi}{\cos \varphi + j e_{rmn} \sin^{2} \varphi}$$

$$r_{2} = e^{j \frac{\lambda_{0} \varphi}{\lambda_{0}} \cdot \frac{d}{\rho_{\nu} \cdot \rho_{\nu}}}$$

$$r_{3} = e^{\frac{j \frac{\lambda_{0} \varphi}{\lambda_{0}} \cdot \frac{d}{\rho_{\nu} \cdot \rho_{\nu}}}{\lambda_{0}}}$$

\( \varphi \) is the angle of the reflected wave, and $d$ is the thickness of the dielectric slab section $mn$ (Fig. 2) with the relative permittivity

$$e_{rmn} = \epsilon_{2mn} / \epsilon_{1}.$$

The numerical image reconstruction is carried out with the inverse discrete FRESNEL transform

$$S_{mnq}(z) = \sum_{l=0}^{L} \sum_{t=0}^{T} e^{j \frac{\lambda_{0} \varphi_{\nu}}{2} \cdot \frac{d}{\rho_{\nu} \cdot \rho_{\nu}}} \cdot e^{j \frac{\lambda_{0} \varphi_{\nu}}{2} \cdot \frac{d}{\rho_{\nu} \cdot \rho_{\nu}}} \cdot e^{j \frac{\lambda_{0} \varphi_{\nu}}{2} \cdot \frac{d}{\rho_{\nu} \cdot \rho_{\nu}}}$$

by which the image function $S_{mnq}$ is calculated for the $mn$ object segments and for a discrete frequency denoted by $q$. For the multifrequency holography technique, a weighted sum of all image functions at $Q$ frequency samples is used. If $I$ and $L$ in (6) are chosen appropriately, standard two-dimensional FFT-subroutines may be used.

3. Results

A glass plate ($\epsilon_{2} = 6.5$) of size 48cm $\times$ 48cm with a thickness of 8mm (Fig. 3a) was chosen for a first example to demonstrate the
Fig. 3 b-e Glass plate ($\varepsilon_r=6.5$). b) Computer simulated hologram using equations (1)-(5). c) Measured hologram. d) Image reconstruction from the simulated hologram, and e) Image reconstruction from the measured hologram using equ. (6). Position of the transmitting antenna (cf. Fig 1): $x_0=1m$, $y_0=2.5m$; sample point distances in the hologram and object plane: $Ax=Ay=8mm$; number of sample points: $M=N=32$. Wavelength $\lambda = 3cm$. Size of the hologram and object plane: $1.92m \times 1.92m$. Distance between object and hologram plane $z_p = 4m$.

Fig. 4 Flexiglass plate ($\varepsilon_r=2.5$). a) Measured hologram. b) Image reconstruction from the measured hologram using equation (6). Data of the measuring equipment and for the reconstruction cf. Fig. 3.

The efficiency of the computer simulation of holograms and the numerical reconstruction of plane dielectric objects by comparison with the corresponding measured results, c.f. Figs. 3b - 3e. The dynamic range of the measured and reconstructed values of about 40dB is displayed by a logarithmic gray scale simulated by corresponding letters of the printer. For the image reconstruction, all points below -24dB of the maximum value are suppressed. Good agreement between computer simulated and measured results may be stated. Moreover, the dielectric plate is clearly imaged at the correct position in its original
A plexiglass plate ($\varepsilon_r=2.5$) of size 48cm x 48cm with a thickness of 20mm chosen for the second example demonstrates (Fig. 4) that a clear image reconstruction (Fig. 4b) from the measured hologram (Fig. 4a) may be obtained using the discrete FREDNELL-Transform(6), also for dielectric plates with low permittivity values.

The efficiency and the limitations of the hologram simulation and image reconstruction method investigated are demonstrated in Figs. 5 for the more complicated plane dielectric object shaped in form of the letters "RW". The dielectric material chosen is glass ($\varepsilon_r=6$) with a thickness of 8mm. The width (12cm, 4A) of the bars of the letter "R" chosen violates the sampling theorem for spatial spectra $^4$ by which the minimum size of the object dimensions $x_{obj}, y_{obj}$ for the chosen data is limited to

$$x_{obj} \geq \frac{2\eta \lambda}{\Delta x_0 L} = 12.5\text{cm}, \quad y_{obj} \geq \frac{2\eta \lambda}{\Delta y_0 L} = 12.5\text{cm} \ .$$

$\eta = 1$ is the first minimum of the spatial sinc-function considered, the distance z and the dimensions $\Delta x_0 L, \Delta y_0 L$ of the hologram plane are the same as in Figs. 3b-e: $z = z_p = 4m$, $1.92m \times 1.92m$. Consequently the image resolution of the letter "R" in Fig. 5c is not of sufficient quality. The clear identification of the letter "W", however, demonstrates the accuracy of the numerical hologram simulation and image reconstruction method presented in this paper.

Fig. 5 Plane dielectric object (glass, $\varepsilon_r=6$, thickness 8mm) shaped in the form of the letters "RW". The small width (12cm, 4A) of the bars of the letter "R" chosen violates the sampling theorem for spatial spectra. The width (18cm, 6A) of the bars of the letter "W", however, meets the sampling theorem. a) Computer simulation of the objects under consideration. b) Computer simulated hologram according to (1)–(5). c) Image reconstruction according to (6). Other simulation and reconstruction data cf. Fig. 3 b–e. Wavelength $\lambda = 3\text{cm}$.

References