HOLOGRAPHIC IMAGING OF MICROWAVE PROPAGATION

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ABSTRACT

A comparatively small plane scanning antenna and a general-purpose microwave spectrum analyzer were used to record two-tone continuous-wave holograms.

Phase differences in the reconstructed holograms and the amplitude data on images extracted from these holograms enabled highly sensitive three-dimensional high-resolution electromagnetic wave propagation imaging and holographic radar imaging.

INTRODUCTION

Targets and Conventional Techniques

Our two targets were to:

(1) Implement highly sensitive three-dimensional high-resolution imaging that covered the indoor reflection, diffraction, and scattering of microwaves; and

(2) Enable wave propagation analysis and holographic radar imaging.

Practical radar imaging systems developed and applied thus far use pulse-modulated, PN-modulated, and chirp waves from the actual and synthetic apertures of directional antennas. These do not, howerer, enable indoor microwave response observation to cover frequency-dependent phenomena and passive measurement. This means that a wide frequency range is required to enhance distance resolution. Single-frequency holographic radar cannot provide sharp imaging due to a limited Fresnel area (range) and image overlap outside the area of focus. This left direct three-dimensional measurement -- the simplest reliable strategy -- where an electric field strength measurement probe is placed at the system to be measured. The strategy has drawbacks, however, in that the measured system is affected by the probe and the operation involved takes much time.

Principle Behind New Hologram Reconstruction Technique

The hologram reconstruction of coherent waves is explained using the diffraction integral proposed by Fresnel and Kirchhoff. Fresnel or Fraunhofer diffraction approximation is used in numeric processing to reduce the amount of time required for calculation. The approximation applied depends on the wave distance. For example the microscopic image obtained through regulating the focus covers the Fresnel area and the camera image the Fraunhofer area in an optical system.

The relationship between the wave source and observed holograms in the Fraunhofer area is as follows:

OF1

The diffraction integral proposed by Fresnel and Kirchhoff is articulated by

$$\underline{\underline{H(x,y)}} = \frac{j}{\lambda}\iint \underline{\underline{I(u,v)}}\exp(-j2\pi\ r/\lambda)/r\ dudv \qquad (1)$$

⇑ [Measured hologram] ⇑ [Wave sources]

Where

$$r = \sqrt{z^2 + (x-u)^2 + (y-v)^2} \qquad (2)$$

The Fraunhofer diffraction approximation is as folows:

$$r \cong z - (ux + vy)/z + (x^2 + y^2)/2z \qquad (3)$$

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and

$$H(x,y) = K(x,y,z)\iint I(u,v)\exp(j2\pi(ux+vy)/\lambda z)dudv \quad (4)$$

$$K(x,y,z) = \frac{j}{\lambda z}\exp(-j2\pi(z/\lambda + (x^2+y^2)/2\lambda z)) \quad (5)$$

f_x expresses the azimuth and f_y the elevation,

$$\begin{cases} f_x = u/\lambda z & : \text{azimuth} \\ f_y = v/\lambda z & : \text{elevation} \end{cases}$$

yielding

$$I(f_x,f_y) = K^{-1}(x,y,z)\iint H(x,y)\exp(-j2\pi(xf_x+yf_y))dxdy \quad (6)$$

The wave source image is calculated and reproduced from hologram data using expression 6.

K (x, y, z), a phase function, provides the data on the phase shift in reconstructed wave source images. Conventional electromagnetic wave photographs involving only wave source strength distribution along the azimuth and the elevation in the Fraunhofer area are based on amplitude information $I(f_x, f_y)$ alone.

We found that using the difference in reconstructed hologram images observed at two adjacent frequencies offsets K (x, y, z) as the phase function, and provides the propagation delay time from $I(f_x, f_y)$ as the wave source to the point of observation. Equation 5 then becomes

$$d[K^{-1}(x,y,z)]_{phase} / d\omega = (z+(x^2+y^2)/2z)/c = \bar{r}/c \quad (7)$$

Where $\omega = 2\pi c/\lambda$ (8)

We propose the three-dimensional measurement of wave source distribution based on this principle.

We show the results of actual microwave propagation analysis and a three-dimensional holography experiment.

INSTRUMENTATION AND MEASUREMENT

Highly Sensitive Microwave Hologram Measurement

Figures 1 and 2 give a block diagram and an exterior view of the microwave hologram measurement system. As shown in Figure 1, holograms on the hologram observation plane are recorded as x and y data representing the vector potential received by the scanning antenna relative to the vector potential received by the fixed antenna. Two general-purpose microwave spectrum analyzers (R3271) are used -- on in fixed antenna reception and the other in scanning antenna reception -- for phase-locked spectrum selection and frequency conversion.

The received signal, resulting from frequency conversion by each spectrum analyzer, is output as an intermediate frequency (21.4 MHz), which is converted to 1 MHz by the second mixer, then vector-detected by the DFT unit.

The microwave hologram measurement system introduced here is capable of receiving radio wave signals radiated at about 10 dBμ/m by means of a small dipole directional antenna and still imaging them for indoor propagation. The spectrum analyzer input signal level ranges from -100 dBm to -140 dBm. Higher sensitivity may be attained with additional equipment such as RF preamplifiers.

Imaging of Indoor Multipath Radio Propagation

Figure 3 shows some indoor imaging results for radio propagation observed using our hologram measurement system. Figure 4 illustrates the observation conditions.

The hologram reconstructed image in Figure 3 shows the observed hologram data H (x, y) recorded in the Figure 1 system after it has been subjected to a two-dimensional Fourier transform (Eq. (6)) followed by frequency differentiation of the image phase information (Eq. (7)).

In Figure 4, a hologram of 11 GHz waves radiated by an aperture type antenna (aperture size 28 cm x 24.5 cm) (4.5 m to the right of the observation plane), and its reflections (2.5 m to the left of the observation plane), are recorded for 64 x 64 points ($\triangle x = \triangle y = 0.45$ cm).

The reconstructed image shown in Figure 3 represents the measurement results for the Figure 4 data in terms of the azimuth (u) and elevation (v) each with a viewing angle of 80 degrees, the propagation strength in terms of height (linear scale), and the relative propagation delay in terms of brightness. The highest peak, on the right, is the antenna radiation, and the second-highest peak, on the left, is the wave reflected by the reflector. Lower peaks are imaged as ceiling and floor reflections.

While this observation aims at measuring the distributions of the spatial strength of the antenna radiation and its reflection, and their delays, three-dimensional radar imaging can be easily accomplished by introducing antenna radiations from the observation plane and recording only their reflections.

Imaging of Indoor Electromagnetic Field Vector

Figure 5 (a) shows three-dimensional computer graphics for the field vector flow of 4 GHz antenna radiation and the reflections measured, in a setup similar to that in Figure 4, by recording a 4 GHz indoor radio propagation hologram and analyzing wave source distributions of the reconstructed image through the action of a spatial propagation function (space-filter).

The field vector image shown in Figure 5 (a) provides a visual three-dimensional representation of the radiation from an aperture type antenna placed on the right, reflection from a reflector diagonally on the left, and the vector flow of reflections from the ceiling, floor, and elsewhere.

Figure 5 (b) shows the results of a similar observation and analysis for 1 GHz waves radiated by an aperture type antenna placed in the center of the room. This field vector image provides a three-dimensional representation of the spherical beam radiated from the antenna aperture and relatively intense reflections from the floor.

CONCLUSION

We have proposed a method which provides a visual rendering of three-dimensional radio wave propagation through dual-frequency passive holographic observation. We have also suggested several possible implementations.

Technology that allows remote three-dimensional measurement and a visual representation of radio wave signals should both facilitate radio wave propagation analysis and lead to further advances in the application of radio wave technologies.

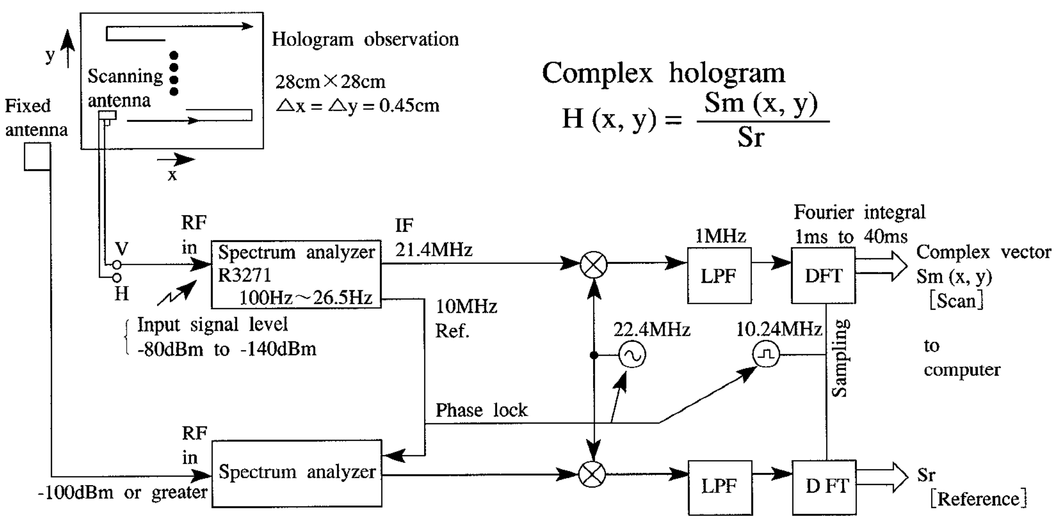


Fig.1 Microwave hologram measurement system.

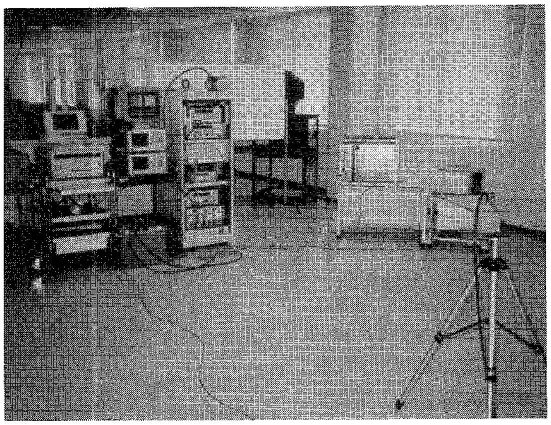


Fig.2 Microwave holography setup.

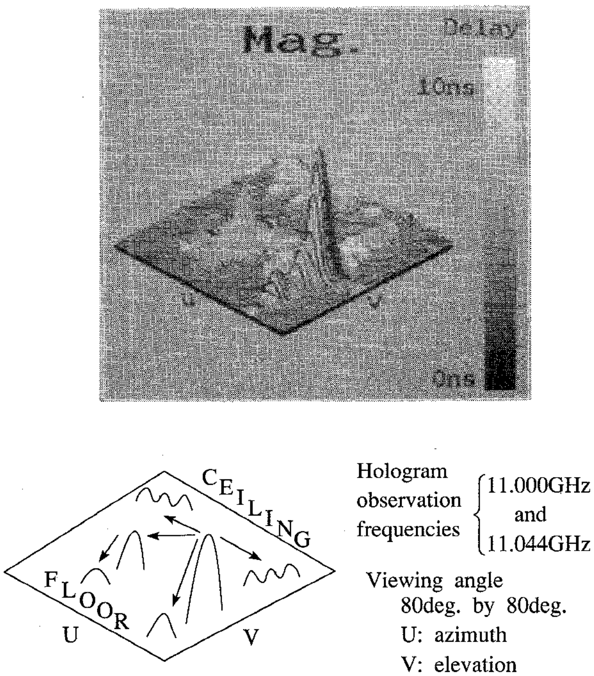


Fig.3 Reconstructed image of indoor radio propagation.
(magnitude and delay U-V plot)

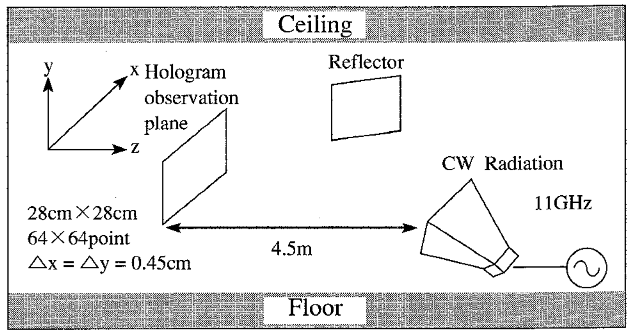
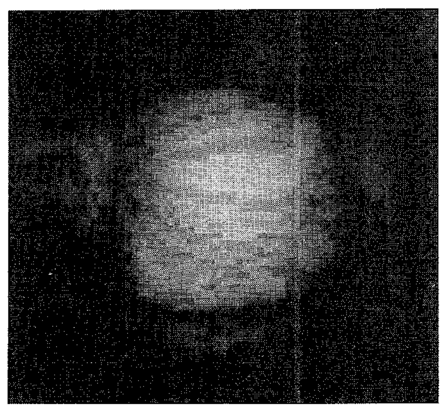


Fig.4 Schematic of geometric configuration.

(a) 4GHz antenna radiation and reflection.



(b) 1GHz antenna radiation.

Fig.5 3D image of field vector.