The use of Indirect Holographic Techniques for Microwave Imaging

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Abstract—This work provides a brief outline of the basic theory of indirect microwave holography. This is supported by experimental work which illustrates how this technique can be used successfully in a number of areas including antenna measurements, concealed weapons detection and medical imaging.

Keywords:- antennas; holography; imaging; antenna measurements

I. INTRODUCTION

The use of microwaves and millimeter waves for imaging is the subject of much current research as they have the potential of providing good quality images in situations not possible with visible light. Techniques employed include the direct equivalent of optical photography[1], the direct and indirect measurement of complex fields and 2D and 3D image reconstruction techniques[2,3,4]. The applications for microwave imaging have ranged from the reconstruction of antenna aperture fields to the detection of concealed weapons and the location of breast cancer tumours.

Apart from the simple replication of photography at microwave frequencies these techniques involve the determination of the complex fields over a 2D plane surrounding, or partially surrounding, the object. From a knowledge of these complex fields 3D images can be reconstructed. Traditionally the measurement of complex field values has required the use of expensive vector analyser equipment. Recently techniques have been developed which have enabled the complex fields to be recorded in a simple and inexpensive manner[5,6]. This work will outline these techniques and will describe preliminary results taken using these techniques in a variety of applications.

II. BASIC THEORY OF INDIRECT HOLOGRAPHY

The basics of microwave holography are similar to optical holographic techniques whereby complex field values are reconstructed from simple intensity measurements. The first stage in this process, the recording of the intensity pattern resulting from the interference between the two waves is termed hologram formation. The second stage is image reconstruction. This reconstruction is used to provide 3D images of the original object.

In general an electromagnetic wave, \( E_a \), can be combined with a reference signal \( E_r \), to provide a two dimensional intensity pattern \( I(x,y) \), to provide a two dimensional intensity pattern.

\[
I(x,y) = |E_a(x,y) + E_r(x,y)|^2
= |E_a(x,y)|^2 + |E_r(x,y)|^2 + E_a^*(x,y)E_r(x,y) + E_a(x,y)E_r^*(x,y)
\]

Taking the Fourier Transform of this gives

\[
F[|I(x,y)|] = F[|E_a(x,y)|^2] + F[|E_r(x,y)|^2]
+ F[E_a^*(x,y)]F[E_r(x,y)] + F[E_a(x,y)]F[E_r^*(x,y)]
\]

Provided the wave, \( E_a \), is band limited and the reference wave, \( E_r \), is of constant amplitude and linear phase shift the above terms can be separated in the spatial frequency domain as shown below.

Figure 1 Separation of terms in Fourier domain

By filtering all but the fourth term and performing an Inverse Fourier Transform we can obtain

\[
I'(x,y) = E_a(x,y)E_r^*(x,y)
\]
Forming the product of this with the known reference signal produces

$$E_r I'(x, y) = \left| E_r \right|^2 E a(x, y)$$  \hspace{1cm} (4)

Which is simply the original complex signal premultiplied by a constant term.

As mentioned previously the ability to separate the terms of the Fourier Transform and accurately reconstruct the original object requires the reference wave to have constant amplitude and linear phase shift. At optical frequencies, $\lambda \sim 500$nm., plane wave conditions apply and a suitable reference signal can be obtained using a radiated wave. The direct transfer of this arrangement to microwave frequencies is not straightforward. At microwave frequencies, $\lambda \sim 0.05$m., the radiated wave can no longer be regarded as a plane wave with linear phase shift and is no longer suitable as a reference signal.

To overcome these difficulties an alternative technique has been adopted for the production of a suitable constant amplitude, linear phase shift reference signal[5,6]. The arrangement for antenna measurements is as shown in Figure 2. In this case the linear phase shift is provided by electronic adjustment of the reference signal fed via the RF cable.

In addition to being able to determine the far field radiation pattern the antenna aperture field can also be reconstructed using back propagation techniques. From a knowledge of the PWS at the measurement plane, $z = 0$, the field at a distance, $z = d$, can be reconstructed using back propagation techniques.

$$E(x, y, z = d) = \frac{1}{2\pi} \int \int A(k_x, k_y) e^{jkz - d} e^{-j(k_x x + k_y y)} dk_x dk_y$$  \hspace{1cm} (6)

For the case of high gain antennas where the radiation covers a restricted angular range it is possible to record results over a Cartesian aperture located close to the aperture plane[7]. Figure 3 shows the holographic intensity pattern for a 600mm parabolic dish antenna measured at 12.7 GHz. In this case a linear phase shift has been applied in the $y$ direction. From this hologram the far field radiation patterns can be obtained and the aperture fields reconstructed following the procedure outlined above. Results in Figure 4 show the $E$ plane radiation pattern for comparison with results taken using direct holography and far field measurements. Also shown in Figure 5 is the reconstructed aperture field using back-propagation techniques following Equation (6). A detailed account of the accuracy achievable using indirect holographic techniques, including probe compensation can be found in [8].

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IV. IMAGING OF PASSIVE OBJECTS

Indirect holographic techniques can also be applied to the imaging of passive objects which do not emit microwaves, in this case the object to be imaged requires illumination using either the same antenna or a second antenna. [9] Hologram formation is carried out in exactly the same manner as for antenna measurements with a linear phase gradient applied in x-axis, y-axis or a combination of both. Image reconstruction has been carried out using simple back-propagation techniques. The following examples illustrate results obtained for a variety of applications.

A. Concealed Weapons Detection

Imaging tests have been carried out at a frequency of 10 GHz, and at a distance of 200mm on a metal gun shaped cut-out covered by a cloth vest as shown in Figure 6. A significant feature of the indirect approach is the ability to reconstruct both amplitude and phase patterns produced by the original object. The clear outline of the metal shape can be seen in Figure 7 (a) Magnitude and (b) Phase.

B. Breast Phantom Imaging

Using a basic paraffin wax breast phantom with an embedded simulated tumour, as shown in Figure 8 imaging results were taken over an aperture 400mm x 400mm with the antennas located at a distance of 35mm from the top of the phantom. Sample spacing was 10mm at an operating frequency of 9.4 GHz. The major difference in this case was that results were taken in an oil bath to eliminate the large reflection which would take place at the surface of a simulated breast in free space. The reconstructed image in Figure. 9 clearly shows the location of the simulated tumour.
C. 3D Imaging

Using holographic techniques it is also possible to reconstruct 3D images of objects. This can be achieved by taking 2 orthogonal holographic intensity patterns and combining the reconstructed images using back propagation techniques. Initial results for a simple dielectric cube, $\varepsilon_r = 2.33$, of side 50mm as shown in Figure 10 were taken over scanning apertures of 400mm x 400mm at a distance of 150mm from the block. Sample spacing was 10mm at a frequency of 10 GHz. Back propagation techniques were used to reconstruct the scattered fields at intervals of 10mm within the 400mm cube. Results from the two sets of reconstructions were then combined to provide the 3D image as shown in Figure 11.

Figure 10 Dielectric block 50mm cube

Figure 11 Reconstructed 3D image of dielectric block

V. CONCLUSIONS

This work has outlined how indirect holographic techniques can be applied to microwave imaging for security and medical applications. A significant advantage of indirect techniques is the fact that only scalar intensity patterns need to be recorded, which can be done in a simple and in inexpensive manner. This work has shown how both magnitude and phase images of objects can be reconstructed from these intensity patterns. It has demonstrated that good quality images of concealed weapons can be obtained. It has also demonstrated the potential of using indirect holographic techniques for medical imaging and for providing 3D images in a simple and inexpensive manner.

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REFERENCES


