Investigation of Resolution Limits for Indirect Microwave Holographic Imaging

O. Yurduseven, D. Smith, , B. Livingstone
School of CEIS, Northumbria University
Ellison Place
Newcastle upon Tyne, NE1 8ST, UK e-mail:
david.smith@northumbria.ac.uk

V. Schejbal
DFJP, University of Pardubice
Pardubice 53210, Czech Republic
e-mail: vladimir.schejbal@upce.cz

Abstract—**This work describes how indirect holography which has previously been applied to the determination of antenna radiation patterns can be adapted for the imaging of passive objects. It provides details of how complex scattered field values can be obtained in a simple and inexpensive manner from sampled scalar intensity measurements taken over a single scanning aperture. This work uses indirect holographic techniques to image a number of simple objects including a rectangular metallic plate, a small metal plate covered by a dielectric sheet and a small metallic circular annulus. This work demonstrates that good quality images can be reconstructed from simple scalar intensity patterns. It demonstrates that clear outlines can be obtained in particular from reconstructed phase patterns and that good images can be obtained from objects with dimensions of the order of a half wavelength.**

Keywords- microwave imaging; microwave holography; near-field microwave imaging; image reconstruction

I. INDIRECT MICROWAVE HOLOGRAPHY

Basic Outline

Indirect holography offers a simple and inexpensive technique for the determination of complex scattered fields using only scalar intensity measurements taken over a single aperture. [1 - 5] Such an arrangement does not require the use of vector measuring equipment and can be performed using basic power measuring devices. An outline of the technique is given below in Fig. 1.

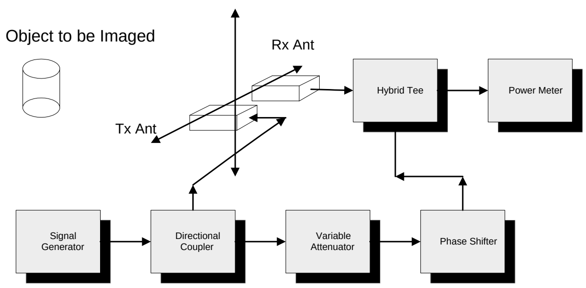


Fig. 1 Outline of Indirect Holographic Imaging System

This signal is applied to one of the inputs to the hybrid tee. A phase coherent reference signal, E_r (x,y), is applied to the second input of the hybrid tee. This reference signal is assumed to have a uniform amplitude and a linearly increasing phase shift which can be applied along the x-direction, along the y-direction or as a combination of both.
The process can be described without loss of generality by considering a one dimensional scan in the x-direction.
In this case the reference wave will be of the form

$$E_r(x) = E_0 e^{-jk_r x} \tag{1}$$

with

$$k_x = \frac{\Delta\varphi}{\Delta x} \tag{2}$$

After illumination the recorded scattered signal from the object will be of the form $E_s(x)$
and the intensity of the output signal from the sum port of the hybrid tee will be

$$\begin{aligned} I(x) &= |Es(x) + Er(x)|^2 \\ &= |Es(x)|^2 + |Er(x)|^2 + Es^*(x).Er(x) + Es(x).Er^*(x) \end{aligned} \tag{3}$$

Taking the Fourier Transform of this expression we obtain

$$\begin{aligned} F\{I(x)\} &= F\left\{|Es(x)|^2\right\} + F\left\{|E_0|^2\right\} \\ &+ F\{Es^*(x)\} \otimes F\left\{E_0 e^{-k_x x}\right\} + F\{Es(x)\} \otimes F\left\{E_0 e^{+jk_x x}\right\} \end{aligned} \tag{4}$$

The first two terms of this expression are centered around the origin in the Fourier domain with the third and fourth terms displaced from the origin by -/+ k_x respectively. This is shown diagrammatically in Fig. 2.

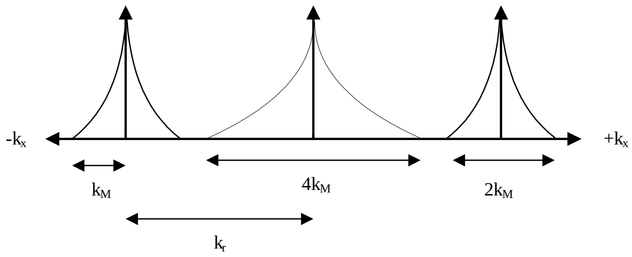


Fig. 2 . Spatial Frequency Spectrum of Intensity Pattern

Provided that the scattered signal can be band limited, $k < k_M$, and subject to being able to apply a suitable phase gradient to the offset reference signal, $k_x > 3.k_M$, the third and fourth terms of equation (3) can be separated and the unwanted terms filtered off. If we restrict attention to the fourth term this will produce a filtered pattern of the form

$$F'\{I(x)\} \quad = \quad F\{E(x)\} \otimes F\{E_0 e^{+jk_x x}\} \tag{5}$$

Centralising this pattern and taking the Inverse Fourier Transform gives

$$\begin{aligned} E'(x) \quad &= \quad F^{-1}[F\{E(x)\}] \\ &= \quad E(x) \quad = \quad E_{0s} e^{-j\theta x} \end{aligned} \tag{6}$$

which is the original complex scattered field at the measurement plane.

From a knowledge of the complex field at the measurement plane images of the scattering object can be obtained following similar back-propagation techniques as described in Sheen [6]

$$\begin{aligned} E'(x, z = -d) \quad &= \quad \frac{1}{2.\pi} \int [F\{E(x)\}] e^{j.k_z.d} . e^{-j.k_x.x} .dx \\ &= \quad E(x) \quad = \quad E_{0s} e^{-j\theta x} \end{aligned} \tag{7}$$

Whilst the technique of off-axis indirect holography has found widespread use at optical frequencies its use at microwave frequencies has been limited due to practical difficulties in producing the required radiated reference signal with linear phase gradient. A method of overcoming this difficulty by using a synthesized reference signal has previously been described for the determination of antenna radiation characteristics. [1-5] This work describes how indirect holographic techniques can be extended to provide complex scattered fields of passive objects and to reconstruct images of the original object. It aims to demonstrate the ability of indirect holography to provide images of objects with dimensions smaller than one half wavelength.

II. INDIRECT MICROWAVE HOLOGRAPHY

Initial tests were conducted on a thin rectangular aluminium sheet, 200mm x 120mm, located 120mm from the scanning aperture as shown in Fig. 3, and at a frequency of 12.5GHz. Results were taken at sample spacing, $\Delta x = \Delta y = 6$mm over a rectangular scanning aperture, 450mm x 450mm. The required offset reference signal was synthesized by introducing a phase shift, $\Delta\Phi = 2.\pi/3$ rads., between sample spacing, $\Delta x = 6$mm producing an offset reference wave vector, $k_r = 349$ rads./m ($k_0 = 261.8$ rads./m).

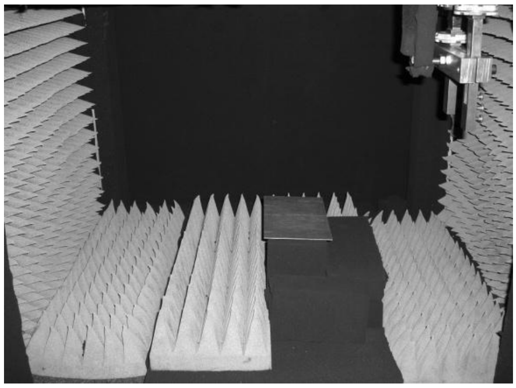


Fig. 3 Holographic Imaging of Metal Plate

Results in Fig. 4 show the recorded holographic intensity pattern over a 450mm x 450mm scanning aperture with a linear phase shift applied along the horizontal axis with horizontal and vertical axes are shown in terms of the sample number.

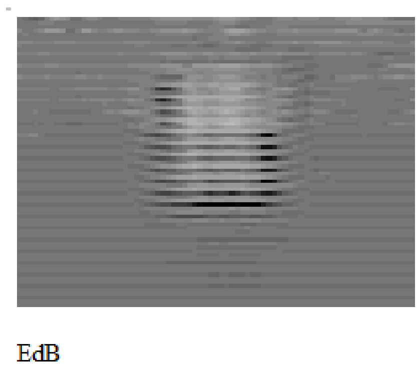


Fig. 4 Holographic Intensity Pattern

The experimental results has been zero filled to a 256 x 256 data array before being transformed into the Fourier Domain to provide results in the frequency domain as shown in Fig. 5.

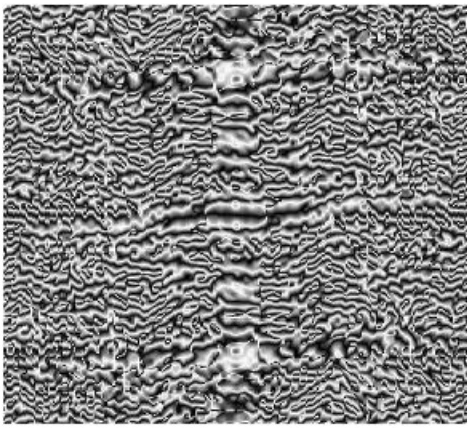


Fig. 5 Fourier Transform of Intensity Pattern

Following the procedure outlined in the previous section and equations (4) - (6) the complex scattered field at the measurement plane can be reconstructed as shown below in Fig. 6.

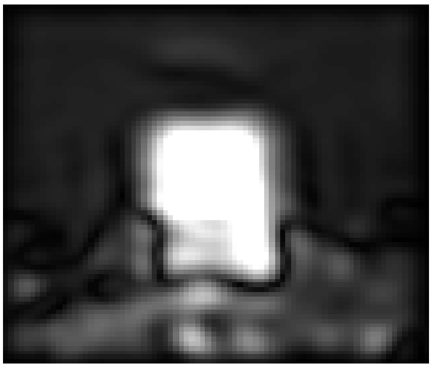


Fig. 6 Reconstructed Image of Metal Sheet

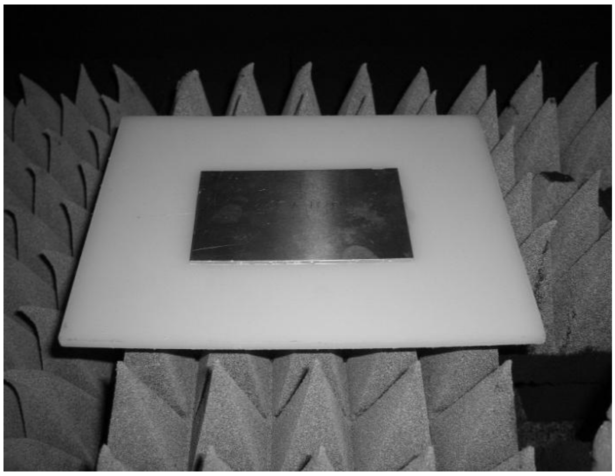
Experimental Results – Imaging of Concealed Objects

III. IMAGING OF CONCEALED OBJECTS

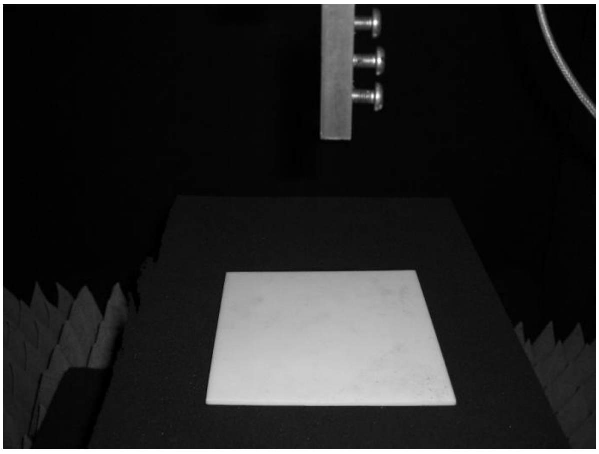
Further tests were undertaken to investigate if this technique could be used to image concealed objects successfully. In this case the test object consisted of a small aluminium plate, 100mm x 60mm, attached to the underside of an 8mm thick sheet of polythene of dimensions, 240mm x 240mm. A view of the test object with the metal side uppermost is shown in Fig. 7 (a). The object was arranged as shown in Fig. 7 (b) with the metal plate under the plastic sheet for holographic imaging.

In a similar manner to the previous section holographic intensity measurements were taken over a scanning aperture, 450mm x 450mm, at a frequency of 12.5 GHz with similar sample spacing and reference phase offset. Reconstructed images at the position of the original object as shown in Fig. 8. As before the horizontal and vertical axes represent the original physical aperture of 450mm x 450mm.

The outline of the metal plate is clearly visible with approximate dimensions 110mm x 75mm together with a loosely defined boundary for the more weakly scattering dielectric cover sheet. These results compare well with the dimensions , 100mm x 60mm, of the original object



(a) Small Metal Plate attached to Dielectric Sheet



(b) Plate Arrangement for Holographic Imaging

Fig. 7 Imaging of Concealed Metal Plate

IV. IMAGING OF CIRCULAR OBJECTS

In order to examine the ability to image curved objects a third test object consisting of a circular metallic annulus of diameter, d_o = 115mm, and internal diameter, d_i = 95mm was used. This annulus formed the outer ring of a small corrugated horn as shown in Fig. 9. At 12.5 GHz the width of this annulus, w = 10mm, was less than half a wavelength ($\lambda / 2$ = 12mm).

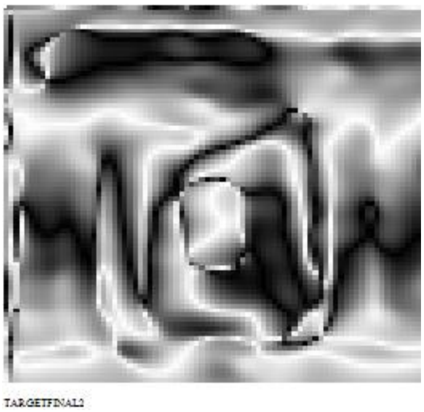


Fig. 8 Reconstructed Image of Concealed Metal Plate under Dielectric Sheet

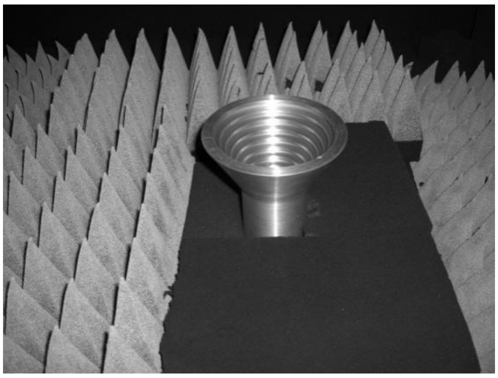


Fig. 9 Imaging of Conical Horn Aperture

Experimental results were recorded in a similar manner to that outlined above. In this case the reconstructed image is as shown in Fig. 10. From Fig. 10 it is possible to discern the outline of the antenna rim and provide an approximate value of diameter , d = 125mm, and a width value, w = 17mm. Also shown for comparison is the outline of the actual horn aperture. The agreement with the original outline is apparent from these results.

V. CONCLUSIONS

This work has provided details of a simple method for the imaging of objects using indirect holography which has been shown able to reconstruct images of objects of less than one half wavelength in dimension.

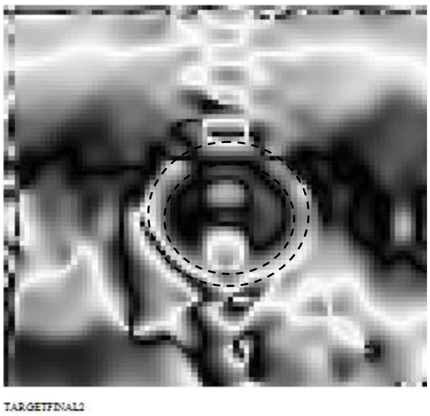


Fig. 10 Reconstructed Image of Conical Horn Aperture

By forming a holographic intensity pattern from the scattered fields and a reference signal with known linear phase shift separation of terms can be achieved in the Fourier Domain. By extracting the required term of the Fourier pattern and performing an Inverse Fourier Transform the original scattered fields at the measurement plane can be reconstructed. Additionally by using back propagation principles the scattered fields at the position of the original object can be reconstructed. Results for a range of simple objects have shown that this technique can provide good quality images. This technique has been shown to be able to provide good images of objects with dimensions less than one half wavelength. Whilst this work has been performed for a single frequency, f = 12.5 GHz., this work can be extended to multiple frequencies and to millimeter wave imaging.

REFERENCES

[1] J. C Bennett, A. P. Anderson, P. A. McInnes and A. J. T. Whitaker, "Microwave holographic metrology of large reflector antennas", *IEEE Trans. Antennas Propag.*, vol. 24, no. 3, pp. 295-302, May 1976.

[2] D. Smith, M. Leach, and A. Sambell, "An indirect holographic method for determining antenna radiation patterns and imaging antenna fields," in *Proc. IEEE Int. Antennas Propagat. Symp. Dig.*, San-Antonio, TX, Jun. 16–21, 2002, vol. 4, pp. 706–709.

[3] D. Smith, M. Leach, M. Elsdon, and S. J. Foti, "Indirect holographic techniques for determining antenna radiation characteristics and imaging aperture fields," *IEEE Antennas Propag. Mag.*, vol. 49, no. 1, pp. 54–67, Feb. 2007.

[4] V. Schejbal, V. Kovarik, and D. Cermak, "Synthesized-Reference-Wave Holography for Determining Antenna Radiation Characteristics," *IEEE Antennas and Propagation Magazine*, 2008, vol. 50, no. 5, p. 71 – 83.

[5] V. Schejbal, J. Pidanic, V. Kovarik, D. Cermak, "Accuracy Analyses of Synthesized-Reference-Wave Holography for Determining Antenna Radiation Characteristics," *IEEE Antennas and Propagation Magazine*, 2008, vol. 50, no. 6, p. 89 – 98.

[6] D. M Sheen, D. L. McMakin and T. E. Hall, "Three-dimensional millimetre wave imaging for concealed weapons detection" *IEEE Trans. Microwave Theory Tech.*, vol. 49, no. 9, pp.1581-1592, 2001,