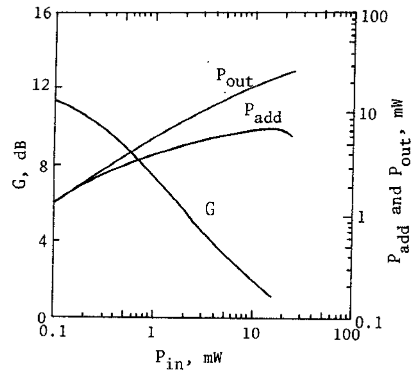

Fig. 4. Variations of gain, output power, and added power with input power at a single operating frequency, 10.5 GHz.

$$P_{out} = G \cdot P_{in} = P_{in} + P_{add}. \quad (5)$$

Fig. 3(b) shows the calculated amplifier frequency response. Here, the reference plane was chosen at the terminals of the diode chip, therefore $Y_d = Y_{eq}$ in (3). For the circuit admittance Y_c, a single-tuned circuit was assumed and the package parasitics were omitted. [Including the package parasitics, such as a pill-prong-type package, the bandwidth of the amplifier was almost equal to that in Fig. 3(b).] The small-signal power gain and the bandwidth at 3-dB down are obtained to be 12.7 dB and 270 MHz, respectively. As the input level is increased, the gain compression occurs and the bandwidth of the amplifier becomes wider as observed in our experimental results [5]. The gain expansion at lower frequencies can be seen, because the susceptance of the diode becomes large with increasing input signal level. It can also be seen that the gain compression with an increasing input level is severe at frequencies where the small-signal gain is high. The variations of power gain, power added, and power output with input power are shown in Fig. 4 at a single operating frequency. The added power reaches a maximum value and falls upon further increasing input power and the saturation of output power and gain compression occur as observed experimentally.

Conclusion

A frequency-independent large-signal equivalent circuit has been proposed for a BARITT diode and is shown to be well applicable to the investigation of the device performance in a practical microwave circuit. This equivalent circuit has only one resistive element. Therefore, the equivalent circuit of our model will be useful for an optimum design of an amplifier for a small-signal case because the reference plane can be chosen at the terminals of this resistive element so that Y_c consists of linear passive elements only.

The equivalent circuit proposed here for a BARITT diode will be applicable to other active devices such as IMPATT's.

References

[1] M. E. Hines, "Negative resistance diode power amplification," *IEEE Trans. Electron Devices*, vol. ED-17, pp. 1–8, 1970.

[2] M. S. Gupta, "Large-signal equivalent circuit for IMPATT-diode characterization and its application to amplifiers," *IEEE Trans. Microwave Theory and Tech.*, vol. MTT-21, pp. 689–694, 1973.

[3] H. W. Bode, "Network analysis and feedback amplifier design."

[4] M. Matsumura, "Large-signal analysis of silicon BARITT diodes," *Electronics and Communications in Japan*, vol. 56, no. 5, pp. 35–36, 1973.

[5] K. Okazaki, N. S. Chang, and Y. Matsuo, "Experimental studies on the large-signal operation of the BARITT-diode amplifiers," *Electronics and Communications in Japan*, vol. 58, no. 5, pp. 29–30, 1975.

High-Quality Image Reconstruction from Double Microwave Holograms

HIROSHI SHIGESAWA, MEMBER, IEEE,
KEI TAKIYAMA, MEMBER, IEEE, AND
MAMPEI NISHIMURA

Abstract—**A new mode of microwave holography is described. This is based upon the simultaneous deconvolution applied to double holograms obtained at different positions in space and has produced markedly improved microwave images. The effectiveness of the present method is demonstrated in both simulations and experiments.**

The technique of microwave holography [1], [2] is of considerable importance for imaging objects obscured by media which are optically opaque but are transparent to microwaves. However, microwave holograms usually have small apertures in terms of the recording wavelength, and thus resolution is severely restricted and the quality of reconstructed images is often poor. In a previous paper [3], a successful application of digital image enhancement was demonstrated to restore the degraded quality of image without recourse to knowledge of the degrading phenomena. However, the image from a microwave hologram suffers from two inherent degradations resulting from the fact that: 1) the hologram data are really a convolution of the correct data with the radiation characteristics of a microwave radiator; and 2) the reconstructed true image is accompanied with a noisy conjugate image in the case of Gabor holograms. To eliminate these unwanted effects,[1] a new mode of holography is demonstrated in this short paper. This technique is based upon the simultaneous deconvolution applied to double holograms obtained at different positions in space and its essence is understood from ordinary holography which is based upon the simultaneous transmitter–receiver-scanned hologram scheme [5] shown in Fig. 1. For simplicity we assume that the object exists on the x_0 axis with a complex reflection function $\sigma(x_0)$. Let a small broad-beam antenna having a directivity $w(\theta)$ in the x–y plane scan on the x axis, while the object is illuminated with CW microwave energy radiated from a sequence of positions along the scanning axis. Here we consider two kinds of holograms that would be obtained on the x_1 and x_2 axes which are parallel to each other. The distance between the x_0 and x_m axes is assumed as y_{0m} ($m = 1,2$). When the returned signal to the antenna from the object is coherently detected with the transmitting wave, the detected signal denoted by $\tilde{h}(x,y_{0m})$ may be expressed with the convolution integrals as follows:

$$\tilde{h}(x,y_{0m}) = a_m[\exp(j\phi_m)\sigma(x) \circledast t(x,y_{0m}) + \exp(-j\phi_m)\sigma^*(x) \circledast t^*(x,y_{0m})], \quad m = 1,2 \quad (1)$$

where $\circledast$ denotes the convolution integral, the asterisk means the complex conjugate, and ϕ_m denotes the constant phase difference between the returned signal and the internal reference wave. In the paraxial approximation, the system propagator

Manuscript received October 17, 1975; revised January 12, 1976.

H. Shigesawa and K. Takiyama are with Doshisha University, Kyoto, Japan.

M. Nishimura is with Maizuru Technical College, Maizuru, Japan.

[1] The possibility of eliminating the conjugate image in a Gabor hologram has been previously suggested by Bragg and Rogers [4] in the field of diffraction microscopy. However, the technique used here is different.

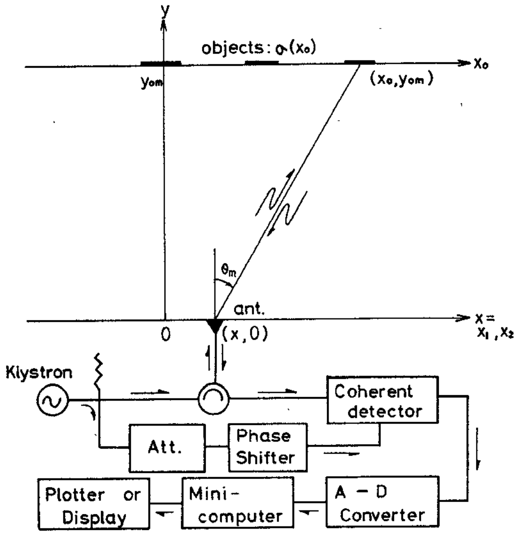

Fig. 1. Experimental setup and the coordinate system for double microwave holography by synthetic aperture.

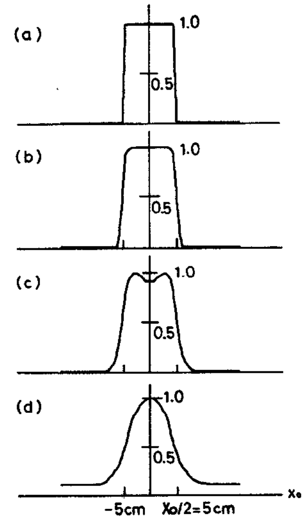

Fig. 2. Simulated results of several reconstruction methods in microwave holography (for the case of an object with the real reflection function).

accompanied by the directivity of antenna becomes

$$t(x,y_{0m}) = w^2(-x/y_{0m}) \exp(-j2\pi x^2/\lambda y_{0m}). \quad (2)$$

As far as the pair of signals of (1) concerns the reconstruction of the image, the complex constant $a_m \exp(j\phi_m)$ in (1) should be carefully adjusted so that $a_1 = a_2 = a$ and $\phi_1 = \phi_2 = 0$ in both $\tilde{h}$. This will be performed practically by introducing a variable attenuator and a variable phase shifter in the reference arm of the coherent detector. Thus, after normalizing (1) by the constant a, we can obtain the pair of holograms as follows:

$$h_1(x) = \sigma(x) \circledast t_1(x) + \sigma^*(x) \circledast t_1^*(x) \quad (3)$$

$$h_2(x) = \sigma(x) \circledast t_2(x) + \sigma^*(x) \circledast t_2^*(x) \quad (4)$$

where $h(x,y_{0m})$ and $t(x,y_{0m})$ is replaced by $h_m(x)$ and $t_m(x)$ respectively, for abbreviation and h_m means $\tilde{h}(x,y_{0m})/a$. This pair of holograms is the essential pair in this short paper. To obtain the true image $\sigma(x)$ from these integral equations, it is effective to apply the Fourier transform (or deconvolution) method, and consequently, $\sigma(x)$ is obtained as follows:

$$\sigma(x) = F^{-1}\left[\frac{H_1(\nu)\cdot T_2^*(-\nu) - H_2(\nu)\cdot T_1^*(-\nu)}{T_1(\nu)\cdot T_2^*(-\nu) - T_1^*(-\nu)\cdot T_2(\nu)}\right] \quad (5)$$

where H_m and T_m are the Fourier transform of h_m and t_m, respectively, and F^{-1} means the inverse Fourier transformation and also ν denotes the spatial frequency. Now it will be noted that the processing of (5) is quite similar to that of the inverse filtering which is often utilized to restore a blurred optical photograph. Thus, considering that the quasi-system transfer function of the present mode of holography, in particular the denominator of right-hand side of (5), contains both influences of the directivity of the antenna and the conjugate image, it may be expected that the desired true image is produced faithfully by the processing of (5) if the pair of holograms, h_1 and h_2, are obtained experimentally.

A number of experiments have been made to verify the theoretical results. The first experiments were performed by the numerical simulations of X-band (9.5-GHz) holography. The simulations were made for two hypothetical objects, one having a real reflection function of $\sigma(x_0) = \text{rect}(x_0/X_0)$, ($X_0 = 10$ cm) as shown in Fig. 2(a) and the other having a complex reflection

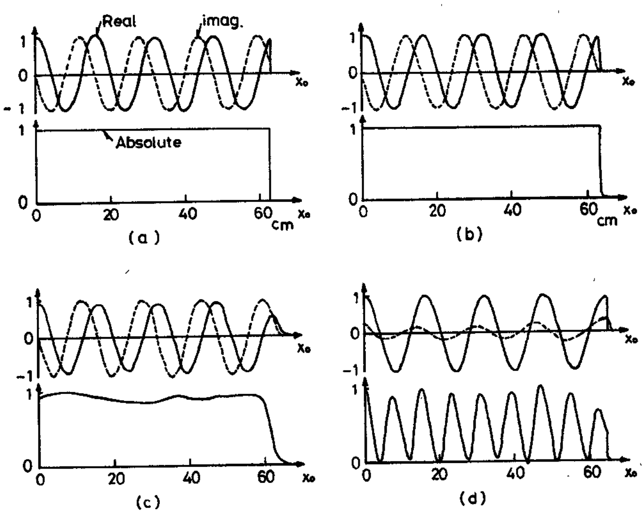

Fig. 3. Simulated results of several reconstruction methods in microwave holography (for the case of an object with the complex reflection function).

function of $\sigma(x) = \exp(-j\pi x_0/8)$ as shown in Fig. 3(a). For the calculation, both objects were sampled at intervals of 1 cm along the x_0 axis. The antenna having an assumed Gaussian directivity, $\exp(-\gamma\theta_m^2)$, was scanned on both $x = x_1$ axis ($y_{01} = 2$ m) and x_2 axis ($y_{02} = 2.1$ m) and the discrete hologram data of 128 points were obtained in the range of $|x| \leq 63.5$ cm for each hologram. Here the directivity constant γ was defined in conjunction with the half beamwidth of the practical antenna employed in the succeeding experiments. Under these conditions, the functional form of the true image is calculated by means of the FFT method and the results fully processed by (5) are shown in Figs. 2(b) and 3(b), while Figs. 2(c) and 3(c) show the true images when the directivity of the antenna is replaced purposely by an unidirectional one only in the stage of reconstruction; that is, the directivity is considered only in the calculation of holograms. This is a version of ordinary imperfect processing for the image formation. From these results, it will be seen that the imperfect processing introduces some degradation in the image by an averaging or smoothing effect, while faithful images of objects are reconstructed by processing according to (5). In particular, it is clearly shown in Fig. 3(b) that the space distributions of both real and imaginary parts of σ are perfectly recovered for the complex object. On the other hand, one of the most simple and ordinary methods to obtain the image from a microwave Gabor hologram is to apply the inverse diffraction transform (the Rayleigh–Sommerfeld scalar theory of diffraction for inverse propagation) to each one of two holograms given by h_1 or h_2. According to this, the image $\tilde{\alpha}(x)$ will be obtained by the following processing:

$$\tilde{\alpha}(x) = F^{-1}[H_m(\nu) \cdot T_m^*(\nu)] \simeq \sigma(x) + \sigma^*(x) \circledast t_m^*(x) \circledast t_m^*(-x). \qquad (6)$$

It is obvious in this method that the true image $\sigma(x)$ is accompanied by a noisy conjugate image as a background noise and then the quality of image will become extremely poor. The reconstructed images by this method are shown in Figs. 2(d) and 3(d), where the recovery of the directivity effect is also overlooked in the stage of reconstruction. These results also represent a version of images obtained by the conventional holography method in which the reconstruction is often performed by neglecting both effects of directivity and noisy conjugate image.

The second set of experiments was performed at 9.38 GHz to verify the simulated results. A small pyramidal horn antenna having a 3-dB beamwidth of 60° in the x–y plane was scanned on both x axes located at $y_{01} = 1.5$ m and $y_{02} = 1.58$ m. The simple object, an aluminum pipe with a diameter of 1.5λ, was placed at $x_0 = 0$ perpendicularly to the x–y plane. Outputs of the scanned coherent detector were sampled at intervals of 0.65 cm along the x axis and the data of 128 points collected over an effective hologram aperture of 83 cm were obtained for each hologram. Fig. 4(a) shows the functional form of the reconstructed true image fully processed by (5). Note that the image is reconstructed with a satisfactory quality as predicted in Figs. 2(b) and 3(b). In these experiments, it is considered to subtract the diffraction field produced by the average transmittance of holograms. Here we again applied the inverse diffraction transform directly to each hologram. The reconstructed images are shown in Fig. 4(b) and are seen to be degraded in quality. Another experiment was made for a reduced data set of 64 points which correspond to a hologram aperture of 42 cm and

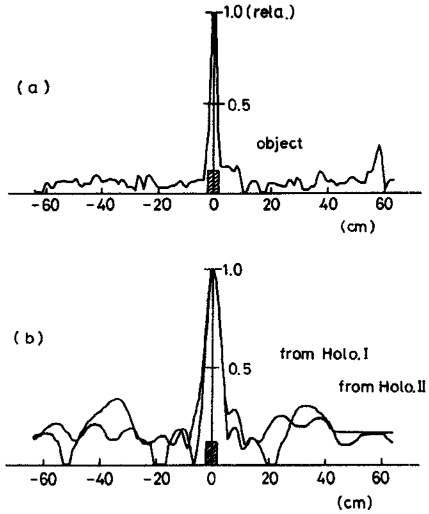

Fig. 4. Reconstructed images obtained in the experiment of double microwave holograms (a) and in the ordinary method (b).

it was satisfactorily proven that the image reconstructed by processing in accordance to (5) is again without any degradations in its quality, while the images obtained by the ordinary method are severely smoothed and of lower resolution where object information is almost lost.

In conclusion, a new mode of microwave holography is presented and its ability to improve markedly the image quality is demonstrated. At present, an application of this technique is planned for the precise measurement of scattering parameters in the diffraction phenomena of electromagnetic waves.

References

[1] R. P. Dooley, "*X*-band holography," *Proc. of the IEEE* (Corresp.), vol. 53, pp. 1733–1735, Nov. 1965.
[2] W. E. Kock, *Microwave Holography, in Holographic Non Destructive Testing.* New York: Academic Press, 1974, pp. 373–403.
[3] H. Shigesawa, K. Takiyama, and M. Nishimura, "An application of digital image processing to microwave holography," *Trans. IECE of Japan* (in Japanese), vol. 57-B, pp. 573–580, Sept. 1974 or *Electronics and Communications in Japan*, vol. 57, Scripta Publishing Co., Sept. 1974.
[4] W. L. Bragg and G. L. Rogers, "Elimination of the unwanted image in diffraction microscopy," *Nature* (Lett.), vol. 167, pp. 190–191, Feb. 1951.
[5] H. Shigesawa, K. Takiyama, T. Toyonaga, and O. Hirao, "Microwave holography by synthetic aperture," *Proc. of the IEEE* (Lett.), vol. 60, pp. 137–139, Jan. 1972.