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IMAGING THROUGH SCATTERING MEDIA WITH GRATING-BASED INTERFEROMETERS

ANTHONY M. TAI and CARL C. ALEKSOFF
Radar and Optics Division

DECEMBER 1980

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20 ABSTRACT (Continue on reverse side if necessary and identify by block number) In this report, the problem of imaging through scattering media is described and the basic approaches to the problem are reviewed. The concept of grating-based interferometers is introduced and some possible configurations are presented. The applications of the grating interferometers in imaging through scattering media are analyzed. The interferometers are basically utilized as coherence discriminators, separating out the scattered components of the received light fields by their coherence properties. The imaging of targets		

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20. Abstract (continued)

Under both monochromatic and wideband illuminations are considered. Experimental results are provided to demonstrate the effectiveness of the concept.

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FOREWORD

This report was prepared by the Electro-Optics Department, Radar and Optics Division of the Environmental Research Institute of Michigan. The work was sponsored by the Army Research Office under Contract No. DAAG29-79-C-0143.

This final report covers work performed between 1 August 1979 and 31 October 1980. The contract monitor was Dr. James Mink of the U.S. Army Research Office, Research Triangle Park, North Carolina 27709. The principal investigator was Anthony M. Tai. Contributors to this effort were Anthony M. Tai, Carl C. Aleksoff, B. Jin Chang and Kim A. Winick.

The view, opinions, and/or findings contained in this report are those of the author(s) and should not be construed as an official Department of the Army position, policy, or decision, unless so designated by other documentation.

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STATEMENT OF PROBLEM

As light waves propagate through the atmosphere, they are perturbed by air turbulence, absorbed by water vapor and ozone, scattered by air molecules (Rayleigh scattering) and larger aerosol particles (Mie scattering). All these effects will degrade the quality of an image transmitted through the atmosphere in various degrees. Particularly detrimental are the effects of air turbulence and scattering by large particles.

When a light field propagates through an aberrating medium such as a turbulent atmosphere, its wavefront is distorted. Various techniques have been devised to measure or estimate [1, 2] the phase distortion and to compensate for it using active optical devices [3, 4]. There are however, few viable solutions for the degradative effect of scattering. The problem of imaging through a scattering media is addressed in this report. Approaches are developed to improve the quality of images obtained through a scattering medium. In particular, the utilization of grating-based interferometers is emphasized.

The presence of aerosol particles in the atmosphere may occur naturally (e.g., fog) or created artificially (e.g., smoke screen). In either case, the aerosol particles scatter part of the light field propagating through its volume. This scattering first of all, reduces the signal energy in the transmission of an optical image. The light energy decreases exponentially with the distance travelled within the scattering medium [5]. That is,

$$I_R = I_0 e^{-\sigma R}$$

where I_0 is the initial intensity of a collimated light beam, I_R is the intensity after travelling through a distance R and σ is the attenuation coefficient. In addition, the light scattered by the

aerosol particles produces a background bias, reducing the contrast or visibility of the detected image. The visibility of the image also decreases exponentially with range such that [6]

$$V_R = V_0 e^{-\sigma_V R}$$

where V_0 is the intrinsic visibility of the target, V_R is the image visibility at range R and σ_V is the visibility attenuation coefficient. Within the visible spectrum, σ is approximately equal to σ_V .

Visibility is defined as

$$V = \frac{I_{\max} - I_{\min}}{I_{\max} + I_{\min}}$$

where $I_{\max}$ and $I_{\min}$ are the maximum and minimum intensities of the detected image. Since

$$I_{\max} - I_{\min} = I_{\text{unscat}} \text{ and } I_{\min} = I_{\text{scat}}$$

where I_{unscat} is the image intensity due to the unscattered portion of the detected light and I_{scat} is the intensity of the background bias, visibility may also be expressed as

$$V = \frac{I_{\text{unscat}}}{I_{\text{unscat}} + 2 I_{\text{scat}}}$$

First, let us consider the case where the light source is placed near the target, the intensity of the unscattered light would be

$$I_{\text{unscat}} = \frac{I_0 r e^{-\sigma R}}{\pi R^2}$$

where I_0 is the intensity of the illuminating beam and r is the reflectance of the target. Since

$$V = V_0 e^{-\sigma_V R} = \frac{I_{\text{unscat}}}{I_{\text{unscat}} + 2 I_{\text{scat}}}$$

and $\sigma_V \approx \sigma$ for visible light, we obtain

$$I_{\text{scat}} = \frac{I_0 r (1 - e^{-\sigma R})}{2\pi R^2}$$

Now consider the case where the light source is placed near the receiver, the illuminating light would have to propagate through the scattering medium to illuminate the target. Assuming that the illuminating light is a collimated beam, then

$$I_{\text{unscat}} = \frac{I_0 r e^{-2\sigma R}}{\pi R^2}$$

The intensity of the scattered light due to forward scattering is equal to

$$I_{\text{F.scat}} = \frac{I_0 r (1 - e^{-\sigma R}) e^{-\sigma R}}{2\pi R^2}$$

Since the illuminating light is located near the receiver, there would also be a tremendous amount of backscattered light. The intensity of the backscattered light is found to be [6]

$$I_{\text{B.scat}} = \frac{G\sigma I_0}{4\pi} \left[\frac{E(2\sigma R_{\min})}{R_{\min}} - \frac{E(2\sigma R_{\max})}{R_{\max}} \right]$$

where

$$E(z) = \int_1^{\infty} \frac{e^{-zt}}{t^2} dt,$$

$R_{\max}$ and $R_{\min}$ are ranges to the farthest and closest scatterers,

and G is the backscattered gain of the aerosol particles relative to isotropic scatterers. Within the visible spectrum, $G \approx 0.24$ [6]. The total intensity of the scattered light would be the sum of the forward and backscattered components. By setting $R_{\max} = R$, we obtain

$$\begin{aligned} I_{\text{scat}} &= I_{\text{F.scat}} + I_{\text{B.scat}} \\ &= \frac{I_0 r (1 - e^{-\sigma R}) e^{-\sigma R}}{2\pi R^2} + \frac{IA}{\pi R^2} \\ &= \frac{I_0 [r(1 - e^{-\sigma R}) e^{-\sigma R} + 2A]}{2\pi R^2} \end{aligned}$$

where

$$A = \frac{G\sigma}{4} \left[\frac{R^2}{R_{\min}} E(2\sigma R_{\min}) - RE(2\sigma R) \right].$$

The visibility of the detected image would be

$$V_R = \frac{I_{\text{unscat}}}{I_{\text{unscat}} + 2 I_{\text{scat}}} = \frac{r e^{-2\sigma R}}{r e^{-\sigma R} + 2A}$$

For example, assuming that $r \approx 0.1$, $V_0 = 1$ and for $\lambda = 0.55 \mu\text{m}$, $\sigma_V = \sigma = 0.8$ (haze). At range $R = 5 \text{ km}$, the visibility of the detected image for the case where the light source is placed near the target would be

$$V_R = e^{-0.8 \times 5} = 1.83 \times 10^{-2}$$

The detected image would therefore have a contrast of 1.83 percent. Since the minimum image contrast required for human recognition is about 2 percent, the target image would be just beyond the visible range.

On the other hand, with the light source placed near the receiver, the visibility of the detected image would only be

$$V_R = \frac{r e^{-2\sigma R}}{r e^{-\sigma R} + 2A} = \frac{3.35 \times 10^{-5}}{1.83 \times 10^{-3} + 21.5} \\ = 1.56 \times 10^{-6},$$

or a contrast of 0.000156 percent. Thus, for this example, the image contrast obtained with the light source placed near the target is 4 orders of magnitude higher than when the light source is placed near the receiver. Gating the system would reduce the effect of back-scattering. However, a very short light pulse would freeze the motion of the scatterers, making continuous averaging impossible. Moreover, if coherence detection techniques are used it is important to realize that the scattered portion of the illumination would also lose its coherence. Only the light that remains unscattered in propagating to and back from the target will maintain its coherent properties. By placing the light source near the receiver therefore would in effect double the volume of the scattering medium. For these reasons, we consider in this report only the cases where the light source can be placed near the target.

Theoretically, if the instantaneous impulse response of the scattering medium can be measured and an inverse filter [7, 8] can be created in real time, it is possible to recreate the target image with the unscattered light. However, it is generally an impossible task to determine the rapidly changing impulse response of a time-varying volume scattering medium. Moreover, no modulator appears to possess the required temporal and spatial bandwidth for the construction of the inverse filter in real time [9]. A more productive approach is to try to separate the scattered and unscattered light and then reconstruct the target image with only the unscattered component.

SUMMARY OF RESULTS

To distinguish between light fields reflected by the target and the scatterers, there must be differences in their physical characteristics that make them separable. We shall divide the approaches into 3 categories according to the physical characteristics used for discrimination. They are: (1) coherence, (2) lateral position, and (3) direction of propagation.

1. Coherence

The phase distribution of the light field scattered by the moving aerosol particles changes with time during the integration period of the detector. In other words, the light scattered by the moving aerosol particles loses its coherence. The scattered and unscattered light fields can therefore be separated by their coherence properties. Four system approaches were examined.

a) Spectral Filtering

Light reflected by the moving scatterers is Doppler shifted. If the scatterers are moved in bulk by high wind along the optical path, the spectrum of the scattered light may be Doppler shifted enough to be filtered out by a narrowband spectral filter. However, high wind speed cannot be guaranteed. Further, a Doppler shift would not be observed from the receiver position if the scatterers are moved laterally across the light path. Brownian motion of the scatterers on the other hand is always present. Their effect would be to increase the spectral bandwidth of the scattered light. It may therefore be possible to discriminate between the scattered and unscattered light by their spectral bandwidths or degrees of temporal coherence. Unfortunately, the Doppler shift due to Brownian motion is very small. The dispersion of velocity due to Brownian motion is given by $\Delta V = \sqrt{kT/m}$, where k is Boltzmann's constant, m is the mass of the

particle and T is the absolute temperature. For example, the average diameter of water droplets in radiation fog is about $10\text{ }\mu\text{m}$. The corresponding mass would be 5.2×10^{-10} grams. At $T = 300^\circ\text{K}$, $\Delta V = 2.8 \times 10^{-6}$ m/sec. The Doppler shifted bandwidth is equal to $\Delta f = 2\Delta V f_0 / C$ where f_0 is the frequency of the light and C is the propagation velocity. Thus, with $\Delta V = 2.8 \times 10^{-6}$ m/sec, we have $\Delta f = 8.9\text{ Hz}$ for $0.6328\text{ }\mu\text{m}$ illumination. The increase in spectral bandwidth due to Brownian motion seems too small to be useful.

b. Holographic Technique

Holographic techniques have been proposed in various times for imaging through fog. Spitz [10] and Stetson [11] independently demonstrated the viability of using the holographic technique and more recently, Lohmann and Schmalfuss [12] expanded on the idea. However, the holographic technique is overly sensitive to mechanical vibrations and air turbulence, severely limiting its practicality in field conditions. The effectiveness and limitation of the holographic technique are analyzed in the paper "Imaging through Scattering Media by Interferometric Techniques," attached in Appendix A.

c. Speckle Interferometer with Dual Aperture Imaging Lens

The stationary target image produced through two apertures at the imaging lens would be spatially modulated [13]. The scattered light on the other hand produces time-varying fringe patterns. Integrating over a sufficiently long period of time, the light pattern due to the scattered light would average into a uniform bias. The modulated image can then be extracted from the bias by bandpass filtering. However, to obtain good SNR with the dual-aperture interferometric system, a trade-off in resolution and efficiency is required. The resolution (or space-bandwidth) requirements of many

applications are not very high, but the sacrifice in light collection efficiency could be very detrimental due to the high attenuative effects of most scattering media. The operation of the dual-aperture speckle interferometer is described in the paper "Speckle Interferometry with an Imaging Grating Interferometer" in Appendix C.

d. Grating Speckle-Shearing Interferometer

This system utilizes high efficiency holographic gratings to split and recombine the light waves. The recombined images is slightly sheared such that stationary fringes will be produced only by the unscattered light waves reflected from a stationary target. The grating interferometric system allows the use of a large numerical aperture and the light gathering efficiency for the aperture approaches 100 percent with the use of volume phase gratings [14]. However, the lateral shearing of the interfering images would produce a slightly blurred edge. The off-axis aberrations associated with the use of gratings may also be a problem if a large field of view is required. The effectiveness of a grating interferometer in imaging through scattering media is analyzed in the paper "Imaging through Scattering Media by Interferometric Techniques," in Appendix A. In the paper, a laser was used to illuminate the target. However, it is only required that the light source be spatially coherent over the sheared distance. Thus, it is also possible to use a wideband point source such as those derived from arc lamp sources for illumination. Since coherent illumination was used, an asymmetric grating interferometer was chosen in the paper. The asymmetric arrangement offers the advantages of simplicity and high efficiency but it is not achromatic when used in the shearing mode. In order to image an object illuminated by wideband light through a scattering medium, a

symmetric achromatic grating interferometer as illustrated in Figure 1 is used. The minimum lateral shear required to decorrelate the scattered portion of the light is equal to the width of the point spread function of the imaging system. In addition, the illuminating light must be spatially coherent over the corresponding sheared distance at the object plane. With the system illustrated in Figure 2, the size of the wideband illuminating light source must be

$$r_0 \leq \frac{0.25 \lambda D}{R}$$

in order for the degree of spatial coherence to be no less than $|\mu_s| = 1/\sqrt{2}$

2. Lateral Position

This type of system produces an image or fringe pattern that is dependent on the lateral positions of the point radiators at the input [15]. If we have a single stationary target radiator with many moving radiators (scatterers) around it, the stationary radiator will form a stationary image point or fringe pattern while the moving scatterers will produce changing patterns. Assuming that the moving scatterers are sparsely populated in the field of view and they are constantly moving into new, never before occupied positions in the field, it can be shown that the SNR will increase by a factor of Vt/S where V and S are the velocity and size of the scatterers and t is the integration time. The system however is much less effective when the scatterers are dense. It is because, as one radiator moves from a particular lateral position in the field of view, another may move into it. In a scattering medium such as fog, both the size and the spacing between the scatterers are beyond the resolution limit of the imaging system and hence, the point spread functions due to the scatterers will merge together to form a

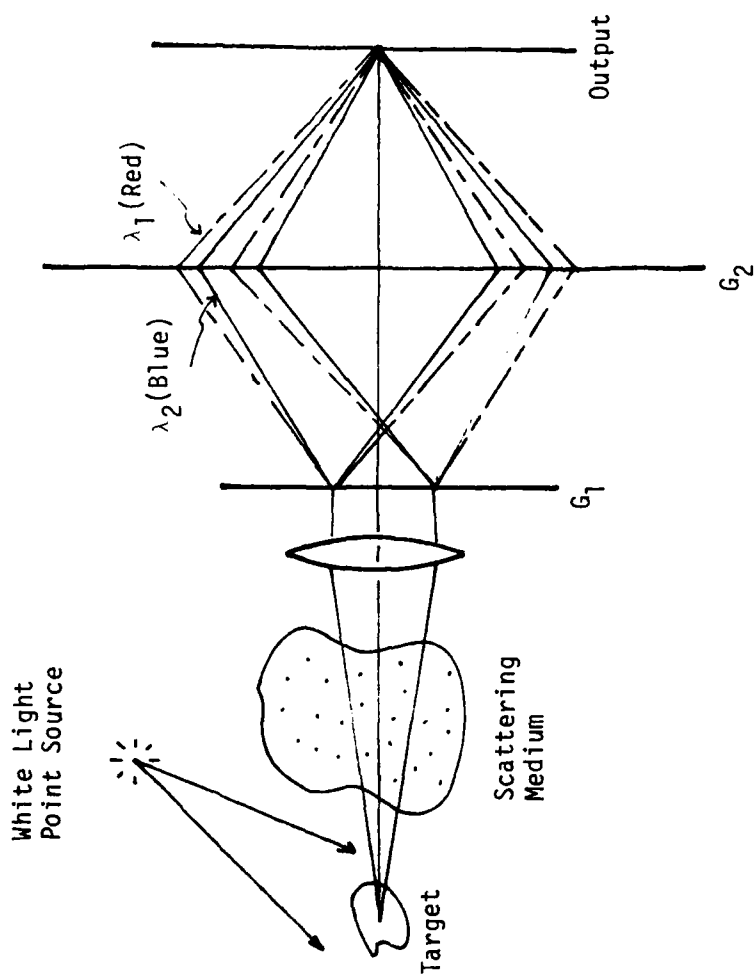


Figure 1. Imagery of a Target Under White Light Illumination Using an Achromatic Grating Interferometer

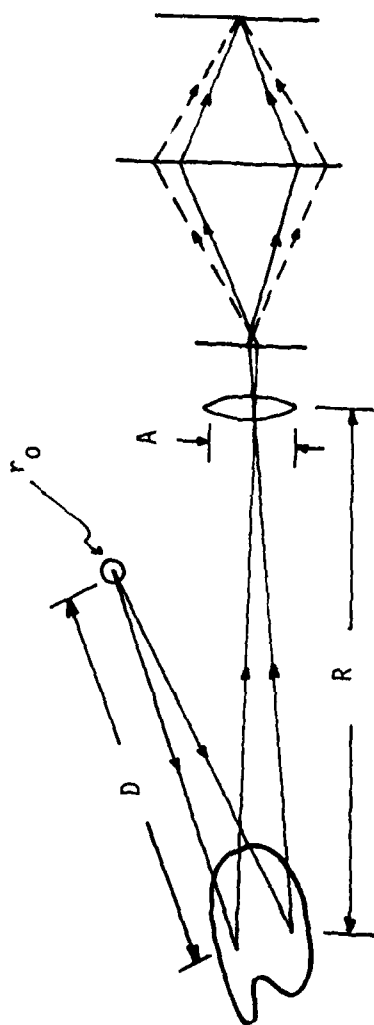


Figure 2. Minimum Source Size Requirement for Shearing Interferometer

stationary continuous intensity image pattern. Time integration under such a condition would not result in any improvement in SNR.

3. Direction of Propagation

In all the approaches described earlier, the separation between the scattered and unscattered light hinges on the fact that the target is stationary while the aerosol particles are moving. Most of the techniques also require the illumination with coherent light since the scattered and unscattered light are differentiated by their coherence properties. We have developed a unique concept utilizing an achromatic grating interferometer that discriminates against the scattered light by the changes in the directions of propagation after scattering.

An achromatic grating interferometer [16] is used to disperse a spectrally wideband light field and then recombined them in a special manner to form an image modulated by achromatic fringes. The conditions for the formation of the achromatic fringes are rather strict. Any deviation from the prescribed light path will destroy the achromatic fringe formation process. Since scattering by the aerosol particles would result in a change in light path, the scattered light would not be able to produce any fringes, contributing only to a uniform background bias.

This system has some unique features. First of all, incoherent light sources such as natural sunlight can be used for target illumination. Secondly, it is not necessary that the target be stationary during the exposure. Since the formation of the fringe pattern is independent of the source position, movement of the target during the exposure would not result in a reduction of fringe contrast. The deleterious effect of target movement is limited to the blurring of the target image in a manner similar to direct imaging. If necessary, the image blur due to such

linear smear can be corrected by various electronic or optical deblurring techniques. Thirdly, since the achromatic grating interferometric system discriminates by the directions of propagation, the system can be effective regardless of whether the scatterers are moving or stationary. Thus, an integration period is not necessary in order to average out the fringe patterns formed by the scattered light. This system would therefore allow the use of very short exposure for each frame (as permitted by the available light level), minimizing any image blur due to object or receiver motion. The disadvantage of this technique is that it requires a grating to be placed near both the transmitting and receiving ends. The system would therefore be more practical as an image transmission system between two cooperative sides than as a target detection system for an uncooperative object.

The operation of the achromatic interferometric system and its utilization for imaging through scattering media is described in the paper, "Transmission of Incoherent Images through Scattering Media Using an Achromatic Grating Interferometer," in Appendix B.

CONCLUSION

Ideally, we would like to have a system that is capable of encoding an uncooperative target under incoherent illumination (e.g., sunlight) and then decoding the received signal in real time to extract the target image from the scattered background noise. We find that such an ideal system is generally not realizable with the approaches studied. Nevertheless, when active coherent illumination of the target is possible, then a significant improvement in the contrast of the target image can be achieved. To discriminate between the scattered and unscattered light by their spatial coherence seems

to be the most effective approach. The system utilizing an achromatic grating interferometer comes closest to an ideal system. It allows the use of wide band light sources for illumination. For transmission applications, some target movement is also permitted.

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LIST OF PUBLICATIONS

Tai, Anthony M., C.C. Aleksoff and B.J. Chann, "Imaging through Scattering Media by Interferometric Techniques," submitted to Applied Optics.

Tai, Anthony M. and Carl C. Aleksoff, "Transmission of Incoherent Images through Scattering Media by an Optical Spread Spectrum Technique Using an Achromatic Grating Interferometer," submitted to Optics Communication.

Tai, Anthony M., "Speckle Interferometry with an Imaging Grating Interferometer," *Optics Letters*, 5, 552, December 1980.

Tai, Anthony M., and Kim A. Winick, "Effects of the Higher Refractive Index on Achromatic Grating Interferometer," submitted to Optics Communication.

Tai, Anthony M. and Carl C. Aleksoff, "Seeing through Fog with an Imaging Grating Interferometer," presented at the Annual Meeting of the Optical Society of America, Oct. 14-17, 1980, Chicago.

LIST OF PARTICIPATING SCIENTIFIC PERSONNEL

Dr. Anthony M. Tai

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Dr. Kim A. Winick (Ph.D., Department of Electrical and Computer Engineering, University of Michigan, December 1980).

APPENDIX A

IMAGING THROUGH SCATTERING MEDIA BY INTERFEROMETRIC TECHNIQUES

A.M. Tai, C.C. Aleksoff and B.J. Chang

Abstract

Imaging through scattering media such as fog is a problem with few known viable solutions. Holographic techniques have been demonstrated successfully in the laboratory but their usefulness is often limited in field conditions by the requirement of a separate coherent reference beam. In this paper, an interferometric imaging technique that utilizes a grating interferometer is presented. Experimental results obtained with this technique show substantial improvement in image contrast over that obtained via direct imaging.

Submitted to Applied Optics.

APPENDIX B

TRANSMISSION OF INCOHERENT IMAGES THROUGH SCATTERING MEDIA
WITH AN ACHROMATIC GRATING INTERFEROMETER

Anthony M. Tai and Carl C. Aleksoff

Abstract

Existing interferometric techniques for imaging through scattering media requires coherent illumination and target stationarity. In this paper, we introduce a new interferometric technique that is capable of imaging an incoherently illuminated target regardless of whether the target and the scatterers are moving or stationary. The system is particularly useful for the high speed transmission of 2-dimensional images through scattering media.

Submitted to Optics Communication.

APPENDIX C

SPECKLE INTERFEROMETRY
WITH AN IMAGING GRATING INTERFEROMETER

Anthony Tai

Abstract

A new speckle interferometric technique utilizing an imaging grating interferometer is introduced. Because the conventional dual aperture is replaced with a set of holographic gratings, the technique offers higher sensitivity and efficiency than existing techniques, and it produces interferograms with an image quality compatible with that obtained by holographic techniques.

Published in Optics Letters, Vol. 5, No. 12, December 1980, pp. 522-524.

APPENDIX D

EFFECTS OF THE HIGHER EMULSION REFRACTIVE INDEX ON
ACHROMATIC GRATING INTERFEROMETER APPLICATIONS

Anthony M. Tai and Kim A. Winick

Abstract

In many holographic applications, the fact that the recording material has a higher refractive index than free space can be ignored. However, when using an achromatic optical system, the higher refractive index of the recording material can be detrimental. The effects of the higher emulsion refractive index on the application of the achromatic interferometer is presented.

Submitted to Optics Communication.

APPENDIX E

SEEING THROUGH FOG WITH AN IMAGING GRATING INTERFEROMETER

Anthony M. Tai and Carl C. Aleksoff

Abstract

Imaging through scattering media such as fog is a serious problem with few viable solutions. Holographic techniques have been demonstrated successfully in the laboratory but their usefulness is limited in field applications by the requirement of a separate reference beam. In this paper, an alternative interferometric technique that utilizes an imaging grating ingerferometer is presented. Experimental results obtained with the proposed technique are also given.

Presented at the 1980 Annual Meeting of the Optical Society of America, Chicago, Illinois, 14-17 October 1980.

