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13. ABSTRACT *(Maximum 200 words)*

The superresolution method was applied to the problem of imaging through inhomogeneities. The process was combined with phase conjugation imaging, thereby producing a very generalized process for imaging through inhomogeneities. In particular, a one-pass phase conjugation process is effectively converted into a two-pass phase conjugation process. In addition, various other related methods for imaging through inhomogeneities were invented, the most successful being a process that combines electronic holography with femtosecond pulse technology.

14. SUBJECT TERMS

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Statement of problem studied

The aim of this grant was to study a method of image formation in which light passing through one path takes on characteristics resulting from the other path. In one embodiment, if the actual path contains a small, resolution-limiting aperture, but the other path does not, then the resolution is as of the light passed through the larger aperture. Alternatively, if the actual path has an inhomogeneity that degrades resolution, then the resolution is again as if the light had passed through the auxiliary path, which has no inhomogeneity, and therefore the inhomogeneity leads to no loss of resolution. The aim is to investigate the capabilites and limitations of this method of imaging through inhomogeneities.

It is a further aim of the grant to relate this method of imaging through inhomogeneites to the well-known method of phase conjugation for imaging through inhomogeneities, comparing the advantages and limitations of each. Another aim was to examine the compatibility of the two techniques, so that a hybrid system could be produced that combines the two into a single system.

Finally, the aim was to carry out an experimental program to give laboratory demonstration of the theories.

Summary of the most important results

Our principal results during this grant have been the following:

1. We formulated a general theory of image formation through inhomogeneities by combining the normally separate processes of phase conjugation and superresolution by incoherent to coherent conversion into a single very general process, using partially coherent light. We carried out an in-depth analysis, and we experimentally verified the theory, showing that under various circumstances, the superresolution techniques by itself in combination with phase conjugation is superior to pure phase conjugation in image formation through inhomogeneities (Cunha and Leith, IEEE J. Quan. El., 1989).

2. We made a very interesting discovery: the superresolution techniques could combine with phase conjugation in such a way that a single pass of the object bearing wave through an inhomogeneity becomes fully equivalent to the usual double-pass method (Cunha and Leith, Opt. Lett., 1988). We carried out an extensive analysis of the process in a very general way. The analysis resulted in a very complicated mathematical expression that simplifed into five special cases, including some of pure phase conjugation, and some of phase conjugation and superresolution in combination. In all cases, the combination of superresolution and phase conjugation gave superior results (Cunha and Leith, J. Opt. Soc. Am. B, 1989). The theory was supported with experimental results.

We think that the use of the superresolution technique to effectively transform the imperfect process of one-pass phase conjugation into the perfect two-pass phase conjugation process is our most significant result.

3. We proposed an improved method of superresolution imaging, in which the reference beam channel could also be an aperture of very small size. This is in contrast to the originally proposed process, in which a full-size reference beam aperture was required (Leith, Opt. Lett, 1990). Most recently, we have experimentally demonstrated this idea.

4. We extended the superresolution, two channel method of imaging through inhomogeneities to the case of arbitrary object beam apertures (aperture size ranging from a δ-function all the way to a full size aperture) and to the case of an arbitrary, distributed inhomogeneity. The analysis is quite involved, but the results are extremely general, and some interesting conclusions result (Chen and Leith, paper in preparation).

5. We considered extending the results to image formation through fibers. The basis for this extension is two-fold. First, a single fiber is, in a sense, just a pinhole with extension along the propagation direction. Thus, any process that allows image formation through a pinhole should also allow imaging through a single fiber. Second, a fiber bundle is essentially a diffuser, in that each fiber in a bundle has a phase delay that is slightly different from that of the other fibers. Thus, any object to be imaged through a fiber bundle must be pressed agains the fiber bundle face, just as an image can be seen through a piece of ground glass only when the object is passed against the glass.

The capability of the incoherent to coherent conversion interferometric process to image through small apertures and though inhomogeneities indicates that this process can overcome both of the above limitations. First, it should be possible to image through a fiber bundle when the object is not against the bundle, which is to say that a 3-D object can be formed into a corresponding 3-D image at the other end of the fiber, and second, it should be possible to form this 3-D image using either many fibers, few fibers, or even a single fiber. We carried out an analysis to verify these suppositions and to determine the limitations. Finally, some preliminary experimental results verify the 3-D image capability. We used a fiber bundle to image a pair of wires, neither at the fiber bundle face. The resulting image showed that each was focused in a different plane, neither plane being at either the entrance or exiting surface of the fiber bundle. In short, we have experimentally demonstrated the capability of 3-D imaging through fiber bundles (Chen and Leith, to be published).

We made a number of auxiliary investigations, in areas that relate to the superresolution imaging technique, and produced the following significant results.

6. We developed a method for producing interference fringes that are perfectly straight and uniformly spaced, even thought the interfering beams are not planar. This is a departure from the conventional case, where for example a pair of spherical wave of equal curvation produces fringes that are only approximately (to 1st order) straight and uniform, and then only in the center of the field. This technique should have application, for example, in the construction of holographic gratings (Hershey and Leith, Appl. Opt., 1990).

7. We developed a very successful method for imaging objects embedded in highly scattering media, such as biological tissue and translucent materials, by combining electronic holography with femtosecond pulse lasers. The method uses electronic holography, performed on the surface of a cooled ccd camera, to gate out and utilize the first arriving light from the scattering medium, i.e., that light which is scattered least and therefore can form the best image of absorbing objects embedded in the medium. Not only can we use the well known capability of holography to perform gating as short as the pulse itself, but we can take advantage of object instability. We make the hologram in a time interval sufficiently short that the medium is stable, which may be a time so short that the signal to noise ratio is poor. We then compensate for the low signal to noise ratio of the image by making many (perhaps hundreds) of holograms in rapid succession, and averaging the images. Since the entire reconstruction process is carried out in a computer, this multiple hologram construction process and subsequent averaging is very easily done. For suitable objects, such as living tissue, each hologram is made within the stability time of the object, but successive holograms are made at time intervals exceeding the coherence time, so that different holograms will have independent speckle, and the averaging process will then drive the noise down. So important is this hologram to hologram instability that in the case of inherently stable media, we actually destroy the stability by, for example, vibrating the medium. Thus, optical path instability, normally extremely detrimental for holography, here becomes an important ingredient (Leith, et. al., to be published in Applied Optics).

Experimental results have been extremely encouraging.

8. We further developed an idea we had conceived for imaging through inhomogeneities. The basic idea published several years ago in Opt. Lett., is to use an achromatic interferometer to form the mutual coherence function of a source distribution, sample the phase and amplitude of the fringe pattern that represents this function, and finally form a set of nonlinear simultaneous equations which are then solved by matrix inversions on a digital computer. In our continuation of this work, we developed an algorithm for solving the equations and we developed some experimental techniques for measurement of the phase and amplitude of the fringe patterns. We thus experimentally verified the theory previously set forth (Chen and Shentu, to be published).

List of Publications

1. A. Cunha and E. Leith, "One way phase conjugation with partially coherent light and superresolution," Opt. Lett. 13, 1105-1107 (1988).

2. A. Cunha and E. Leith, "Generalized phase conjugation system using partially coherent light," IEEE J. Quan. El., 25, 351-359 (1989).

3. E. Leith, R. Hershey and H. Chen, "Technique for high quality fringe generation," Proc. SPIE, Vol. 1211 (1990).

4. E. Leith and A. Cunha, "Holographic methods for imaging through an inhomogeneity," Opt. Eng. 28, 575-579 (1989).

5. A. Cunha and E. Leith, "Generalized one way phase conjugation systems," J. Opt. Soc. Am. B, 6, 1803-1812 (1989).

6. E. Leith, H. Chen, Y. Chen, A. Cunha, D. Dilworth and J. Lopez, "Reduced coherence holography and related methods for imaging into inhomogeneities," Proc. SPIE, Vol. 1212 (1990).

7. R. Hershey and E. Leith, "Grating interferometers for producing large holographic gratings," Appl. Opt., 29, 937-943 (1990).

8. E. Leith, "Small aperture, high resolution, two channel imaging system," Opt. Lett., 15, 885-887 (1990).

9. E. Leith, C. Chen and A. Cunha, "Image formation through inhomogeneities," Proc. SPIE, Vol. 1396, 80-84 (1990).

10. E. Leith, P. Lyon and H. Chen, "Imaging problems with femtosecond-pulse holography," to appear in J. Opt. Soc. Am. A, 8, July 1991.

11. E. Leith, H. Chen, Y. Chen, D. Dilworth, J. Lopez, R. Masri, J. Rudd and J. Valdmanis, "Electronic holography and speckle method for imaging through tissue using femtosecond gated pulses," accepted for publication in Applied Optics, 1991.

12. H. Chen and L. Shentu, "Achromatic interferometer for imaging through turbulence," accepted for Applied Optics.

13. P. Sun and E. Leith, "Superresolution imagery through pinhole apertures," in preparation for submission to Applied Optics.

14. C. Chen and E. Leith, "General two-aperture methods for imaging through distributed inhomogeneities," in preparation for submission to Applied Optics.

15. C. Chen and E. Leith, "3-D image formation through optical fibers," in preparation for submission to Applied Optics.

16. E. Leith, "Holographic methods for image formation through inhomogeneous media," paper presented at Conference on Signal Theory and Image Processing, Cetraro, Italy, May 26-31, 1991, to be published in proceedings of conference due December 1991.

17. E. Leith, "Some challenging problems of holography and their solutions," paper to be presented at International Holography Display Conference, July 15-19, 1991, and paper to appear in SPIE Proceedings.

Scientific personnel supported by this grant:

Paul Lyon
Robert Hershey (Ph.D. in 1989)
Pang-Chen Sun
Hsuan Chen
Andre Cunha (Ph.D. in 1989)

Inventions

We made many patentable inventions, but through publication they have gone into the public domain. One important exception is the electronic holography method for imaging into inhomogeneities. We made a disclosure on this and submitted it to the University of Michigan Intellectual Properties Office.