Fiber Optic Applications in Holographic Interferometry and Laser Speckle Photography

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ABSTRACT

Fiber optics, available as both individual fibers and coherent arrays of many thousands of fibers, provide convenient new tools for the transmission and manipulation of coherent light from a laser. This paper reviews the many applications of these flexible optical components to two popular coherent light techniques for measuring displacements and deformations, laser speckle photography and holographic interferometry.

Introduction

In recent years many investigators have, with some significant success, explored the applications of optical fiber elements to holography[1-7] and holographic interferometry.[8-19] Applications have also been demonstrated to white light or "artificial" speckle photography[20-21] and laser (coherent light) speckle photography,[22-26] albeit in the latter case with objective speckle only. These studies have demonstrated that individual single mode optical fibers provide practical flexible illuminators for both coherent light techniques, while coherent optical fiber bundles may be used to carry holographic or speckle "images" from remote or inaccessible locations to a local station for observation and/or recording and analysis.

Fiber Optics

The functional characteristics of an optical fiber are determined by its refractive index distribution, which is designed to guide light along the fiber by internal reflection or refraction. In its most elemental form an optical fiber may consist of a solid uniform core of highly transparent dielectric material whose refractive index, n_{co}, is slightly higher than the refractive index, n_{cl}, of the cladding which surrounds it. In such a "step index" fiber a light ray traveling down the core will be guided along it so long as its angle of incidence to the core-cladding interface is smaller than the critical angle for internal reflection defined by Snell's law. Any ray propagating at a larger angle will be at least partially refracted out into the cladding on each reflection and soon disappear. Similar arguments may be applied to fibers with more complex but radially symmetric index distributions in which light rays follow curved paths as they are refracted back and forth along the fiber core. In all cases rays propagating at too great an angle will be lost, while rays at shallower angles will be guided. Actually, not every ray propagating at less than the critical angle will be guided by a given fiber. In a rigorous analysis the wave (rather than ray) characteristics of light, described by Maxwell's relations, give rise to a discrete family of guided wavepaths or modes for a specific fiber design excited at a particular wavelength. While there may be many hundreds or even thousands of modes propagating in a given optical fiber, it is possible to design and manufacture fiber which will guide but one. The choice between such single mode fiber and multimode optical fiber for use in holo-interferometry or speckle metrology systems is important. In general, individual single mode fibers make excellent components for transmitting and manipulating coherent light from a laser. They are relatively insensitive to motion along their length, unlike multimode fibers, and they can provide a clean, spatially filtered Gaussian output. Consequently, they make excellent illuminators. On the other hand, they cannot transmit an image, which generally requires a coherent bundle of optical fibers. At the present time such "imaging" bundles are manufactured only from multimode fibers. Consequently, they must be completely immobilized during operation to assure phase stability comparable to that of single mode optical fiber. Nevertheless, such multimode fiber optic elements can transmit images, and provide useful tools for accessing remote or physically obscured test subjects, as will be described.

Holographic Systems with Fiber Optics

Figure 1 shows a diagram of a holographic system in which single mode optical fibers are used to provide object and reference beam illumination. In addition to providing both simplicity and flexibility, the use of fiber optics makes it relatively easy to match optical paths simply by providing fibers of appropriately different lengths. Fig. 2a shows a time averaged holographic interferogram of a vibrating cantilever beam recorded using such a holographic system. So long as the beam splitter and launch optics assembly is firmly mounted to the laser, and the optical fiber outputs, the test subject and the hologram itself are maintained in their relative positions, vibrations or displacements along the fibers themselves will have minimum effect on the operation of the system. In such systems the laser source need not be located on the vibration isolated optical bench, or in the same room (or even building, for that matter) as the test subject and hologram.

In this first example the object wavefront travels by direct line-of-sight from the fiber optic illuminated test subject to the hologram plane. However, in many cases the test subject may not be so conveniently situated, and it would be very useful to use flexible optical fiber elements to both illuminate the observed or remote test subject and to transmit the resulting object wavefront information back to the local test station for recording in a hologram or holo-interferogram. Fig. 3 shows the schematic of such a system used to record Fraunhofer (farfield) holograms using an "instant" holocamera system, and Fig. 4 shows the resulting real-time holo-interferometric fringe field describing the out-of-plane displacement field of a centrally loaded clamped disk as described in (18). Of course the same system may be used in double-exposure holo-interferometry or, as shown in Fig. 2b, time averaged holo-interferometry. With the addition of an image bundle output lens, image plane holograms and holo-interferograms may also be recorded as described in (10). Such systems may be used to carry out holo-interferometric measurements on objects which are submerged, perhaps in an enclosed immersion tank as suggested in Fig. 5. Fig. 6 shows holographic fringe fields describing the out-of-plane deflection of a cantilever beam obtained both in air and underwater, and both on and off the vibration isolated optical bench using a fiber optic system much as described in (12). Without the fiber optic imaging bundle to pierce the free liquid surface, the underwater experiments would have yielded nothing, especially in the nonisolated case. Of course, in all of these experiments the image bundle must be kept relatively immobile — any significant disturbance during an experiment will induce changes in the modal propagation characteristics of the multimode optical fibers and disturb or destroy the hologram correlation. One way around this problem is to use a very short exposure time in recording the hologram, much as in stop-action photography. Such recordings can be made using a pulsed ruby laser coherent light source with a 20 nanoseconds duration and a system of multimode fiber optic bundles for both illumination and remote imaging as described in (7). However, such fiber optic pulsed laser holography is difficult to apply to interferometry unless the dynamic event being measured occurs on a significantly faster time scale than that of any ongoing disturbance of the fiber optics. On the other hand, the use of ultra low spatial frequency (ULF) holography can provide stability for the measurement of deformation in hostile environments where relatively fast moving disturbances of significant amplitude are to be expected. As demonstrated in (13) and (14), such an approach involves using the multimode image bundle to transmit an image of the hologram, which is an intensity distribution with encoded phase information, rather than an image of the test subject, which involves both intensity and (fiber optic displacement sensitive) phase information. Transmitting such a hologram image really means transmitting a complex interference fringe pattern whose spatial frequencies must lie within the relatively low resolution range of even a high quality multimode image bundle. This means that the successful application of a flexible (and possibly moving) multimode image bundle to transmit a hologram requires generating an ultra low frequency interference pattern at the "remote" location of the test subject. In turn, this requires that both the illumination and reference beams be transmitted to the "remote" location, and furthermore that the intersection angle between the reference beam and the propagation direction of the object image wavefront be very small, less than half a degree. Figure 7 shows a schematic of such a ULF holography system. Here two single mode optical fibers of appropriate lengths are arranged to transmit coherent illumination and reference beams to the subject, and a large diameter (10 mm) multimode image bundle capable of resolving around 33 lines/mm is used to return the ULF standing wave interference pattern. Figure 8 shows a reconstruction of a doubly exposed ULF holo-interferogram of an end loaded cantilever beam recorded both directly and by contact printing the intensity pattern at the output end of the image bundles directly onto a film plate. Although there is some unavoidable loss of resolution and contrast associated with the use of this system, no motion isolation is required for any of the optical fiber components.

Fiber Optic Speckle Photography

If a fiber optic arrangement like that used to record remote holograms (Fig. 3) is operated without the reference beam, the resulting image will be that of the test object with a superimposed speckle pattern associated with the coherent illumination. So long as the characteristic size of the speckle is sufficiently large as to be resolved by the multimode imaging bundle, it too can be transmitted as an amplitude distribution without concern for stability. Since this speckle pattern acts as a random grating which moves with the surface, recordings of successive patterns obtained directly or through a fiber optic system provide another means of following the inplane motion of a remote surface. The requirement that the speckle pattern be resolvable by the image bundle is most readily satisfied by using either coarse "artificial" or "white light" speckle or, with the input lens removed, using "objective" or "farfield" laser speckle. Since the effective average size of such speckle patterns must, of necessity, be rather large, they are better suited to photo-electronic recording, digitization and numerical correlation by computer than to the classical methods of speckle photography and optical correlation. As shown in (21), numerically correlated fiber optic white light speckle data can provide meaningful full field in-plane displacement data, albeit at relatively low sensitivities, while in (22-26) it has been demonstrated that objective laser speckle data can be numerically correlated to provide pointwise in-plane displacement information over a significantly greater range of sensitivities.

Summary

In holographic applications fiber optic components may be used in three ways. Individual single mode fibers may be used to provide object beam illumination for the test subject and/or reference beam illumination for the hologram itself. In either case, flexible optical fibers provide convenience and simplicity. Moreover, single mode fibers are considerably more effective than multimode fiber optics because of their far lower spatial noise and greater stability.

In addition to their advantages as convenient illuminators, fiber optic components may also be used to transmit the reflected wavefront back from the test object to the hologram. Adding this fiber optic link facilitates access to test surfaces that may otherwise be optically inaccessible or physically remote from the laser bench or test station where the hologram is to be recorded, and raises the prospects of designing a flexible holographic "probe". Such a sophisticated system would incorporate fiber optics for both illumination and return imaging, analogous to a medical endoscope but with holographic and even holo-interferometric capabilities of great potential value in experimental mechanics. Unfortunately, complete success is not yet here. The need to transmit an image requires that this third flexible fiber optic link be a coherent fiber optic image bundle. Since all such bundles presently available are constructed from thousands of fine *multimode* optical fibers, they are significantly less stable (for holographic applications) than are the single mode fibers used for illumination. This means that, with any combined single and multimode fiber optic holography system wherein the multimode fiber bundle must transmit both amplitude and phase information, considerable care must be taken to secure the full length of the multimode fiber bundle against the deleterious effects of mechanical movement or vibration. Otherwise, such motions produce changes in the multimode fiber bundle's modal propagation characteristics during recording which degrade or completely eliminate the hologram. Nevertheless, such systems have been operated successfully both to record remote holograms and to make remote interferometric measurements by the time-averaged, double exposure and real time holo-interferometric techniques.

The use of short exposure durations, as with a pulsed laser, has been demonstrated as another means of overcoming stability problems in so far as recording remote holograms is concerned, but cannot be expected to provide much relief when doing interferometry for all except those events which occur on a time scale shorter than that of the offending multimode fiber bundle disturbances. On the other hand, mixed mode holographic systems which do not entail the transmission of phase information via the multimode fiber bundle, such as remotely generated holograms of ultra-low spatial frequency, are quite stable and effective for both holography and holographic interferometry. However, the development of a true ULF probe system would be geometrically challenging and require a multimode fiber bundle of both a large cross-section and the best possible resolution to provide both an acceptable signal-to-noise ratio and bandwidth needed for reconstructing complex wavefronts and/or interference patterns.

Speckle correlation techniques, like holographic interferometry, can also benefit from the use of single mode fiber illuminators, although in this case only one such fiber optic link is required (there being no reference beam in speckle metrology). Indeed, many of the same things may be said about single versus multimode optical fibers for speckle applications that were said for holographic applications. However, speckle images may best be treated simply as intensity distributions which move with the test subject and nothing more. In this case the returning image stability requirements are greatly reduced and the multimode fiber bundle resolution becomes most important (as for the remote ULF holography). This is so because the resolution limit establishes the minimum usable characteristic speckle size of any remote speckle field to be transmitted via the multimode fiber bundle. Current experience with commercially available multimode fiber bundles of intermediate cost and resolution require speckle patterns of relatively large characteristic size (at least 50μ) which can readily be generated using unimaged objective laser speckle at the input end and, on the output end, imaging into a vidicon camera/digitizer system for recording and numerical correlation. For a given objective speckle size, such a numerical correlation system can readily measure inplane displacements over a much wider range than can be achieved by optical correlation methods, but is limited to point-by-point studies (unless developed from arrays of illuminating single mode fibers or some sort of scanning illumination system). On the other hand, remote full field measurements can be made using coarse "white light" or artificially painted speckle fields. These can be imaged into a multimode fiber bundle and fed into the vidicon camera/digitizer for subsequent numerical analysis of displacements over a field of view. Both of these approaches permit making comparisons between a succession of states or surface positions so that time histories can be obtained. Furthermore, the use of higher resolution multimode fiber bundles and more (light) sensitive vidicon camera systems should facilitate the application of fiber optics to *subjective* laser speckle metrology which would provide the advantages of both coherent light speckle and full field displacement measurement via a flexible probe system.

Acknowledgements

The authors wish to acknowledge the support of AT&T Bell Laboratories, Murray Hill, New Jersey, the U.S. Army Research Office under Contracts DAAG 29-80-K-0028, DAAG 29-84-K-0183, and the National Science Foundation under Grant No. MEA-8305597.

REFERENCES

[1] Nishida, N., Sakaguchi, M., and Saito, F., "Holographic Coding Plate: a New Application of Holographic Memory," Appl. Opt., 12, 7 (1973).

[2] Rosen, A. N., "Holographic Fundoscopy with Fiber Optic Illumination," Opt. and Laser Tech., 7, 3 (1975).

[3] Hadbawnik, D., "Holographische Endoskopie," Optik, 45, 1, 21-38 (1976).

[4] Suhara, T., Nishihara, H., and Koyama, J., "Far Radiation Field Emitted From an Optical Fiber and Its Applications to Holography," Trans. of the IECE of Japan. Sec E (Engl), 60, 10, 533-540 (1977).

[5] Leite, A.M.P.P., "Optical Fiber Illuminators for Holography," Opt. Commun., 28, 3, 303-306 (1979).

[6] Yonemura, M., Nishisaka, T., and Machida, H. "Endoscopic Hologram Interferometry Using Fiber Optics," Appl. Opt., 28, 9, 1664-1667 (1981).

[7] Dudderar, T. D. and Gilbert, J. A., "Fiber Optic Pulsed Laser Holography," Appl. Phys. Let., 43, 8, 730-732 (1983).

[8] Gilbert, J. A., and Herrick, J. W., "Holographic Displacement Analysis with Multimode-Fiber Optics," Exp. Mech., 21, 8, 315-320 (1981).

[9] Gilbert, J. A., Schultz, M. E. and Boehnlein, A. J., "Remote Displacement Analysis Using Multimode Fiber-optic Bundles," Exp. Mech., 22, 10, 398-400 (1982).

[10] Gilbert, J. A., Dudderar, T. D., Schultz, M. E., and Boehnlein, A. J., "The Monomode Fiber - A new Tool for Holographic Interferometry," Exp. Mech., 23, 2, 190-195 (1983).

[11] Rowley, D., "The Use of a Fiber-Optic Reference Beam in a Focused Image Holographic Interferometer," Optics & Laser Tech., 15, 4, 194-198 (1983).

[12] Gilbert, J. A., Dudderar, T. D., and Nose, A., "Remote Displacement Analysis Through Different Media Using Fiber Optics," Proc. of the 1983 Spring Conf. on Exp. Mech., SESA, Cleveland, OH, May 15-19, 424-430 (1983).

[13] Dudderar, T. D., Gilbert, J. A., and Boehnlein, A. J., "Achieving Stability in Remote Holography Using Flexible Multimode Image Bundles," Appl. Opt., 22, 7, 1000-1005 (1983).

[14] Gilbert, J. A., Dudderar, T. D., and Boehnlein, A. J., "Ultra Low-Frequency Holographic Interferometry Using Fiber Optics," Optics and Lasers in Eng. 5, 1, 29-40 (1984).

[15] Jones, J. D. C., Corke, M., Kersey, A. D., Jackson, D. A., "Single-Mode Fiber-Optic Holography," J. Phys. E: Sci Instrum, 17, 271-273 (1984).

[16] Dudderar, T. D., Gilbert, J. A. Franzel, R. A., Schamell, J. H., "Remote Vibration Measurement by Time Averaged Holographic Interferometry," Proc. of the Fifth Int'l Cong. in Exp. Mech., Montreal, to be presented June 14, 1984.

[17] Hall, P. M., Dudderar, T. D., and Argyle, J. F., "Thermal Deformations Observed in Leadless Ceramic Chip Carriers Surface Mounted to Printed Wiring Boards," IEEE Trans. Components, Hybrids and Manufacturing Technology, CHMT-6, 4, 544-552 (1983).

[18] Dudderar, T. D. and Gilbert, J. A., "Real-Time Holographic Interferometry Through Fibre Optics," J. Phys. E: Sci. Instrum, Vol. 18 (1985).

[19] Dudderar, T. D., Hall, P. M. and Gilbert, J. A., "Holo-interferometric Measurement of the Thermal Deformation Response to Power Dissipation in Multilayer Printed Wiring Boards," accepted for publication in Experimental Mechanics.

[20] Gilbert, J. A., Dudderar, T. D. and Bennewitz, J. H., "The Application of Fiber Optics to Remote Speckle Metrology Using Incoherent Light," Optics and Lasers in Eng., 3, 3, 183-196, (1982).

[21] Dudderar, T. D., and Gilbert, J. A., "Fiber Optic Measurement of the Deformation Field on a Remote Surface Using Numerically Processed White-Light Speckle," Appl. Opt., 21, 19, 3520-3527 (1982).

[22] Dudderar, T. D., Gilbert, J. A., Boehnlein, A. J., and Schultz, M. E., "Application of Fiber Optics to Speckle Metrology - a Feasibility Study," Exp. Mech. 23, 3, 289-297 (1983).

[23] Bennewitz, J. H., Dudderar, T. D., and Gilbert, J. A., "Objective Speckle Measurement," Proc. of the 1983 Spring Conference on Exp. Mech., SESA, Cleveland, OH, May 15-19, 113-118 (1983).

[24] Dudderar, T. D., Gilbert, J. A. and Bennewitz, J. H., "Numerical Correlation of Remote Objective Speckle Patterns for Displacement Measurement," Proc. of the Fifth International Congress on Exp. Mech., Montreal, June 13, 1984.

[25] Dudderar, T. D., Gilbert, J. A. and Bennewitz, J. H., "Displacement Sensitivity in- Remote Objective Speckle Metrology," (Submitted to Exp. Mech.).

[26] Dudderar, T. D., Gilbert, J. A., Bennewitz, J. H., and Van Rossum, E. J., "Remote Objective Speckle Displacement Sensitivity," Proc. of the 1984 Fall Conference on Computer Aided Testing and Modal Analysis, SEM, Milwaukee, WI, Nov. 4-6, 1984.

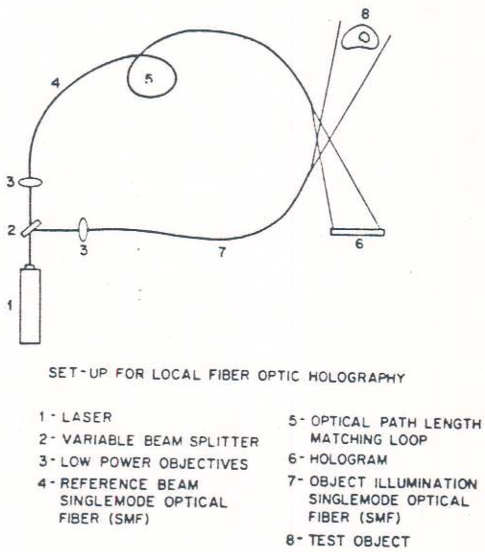

Figure 1. Schematic Diagram of a Holographic System with Single Mode Fiber Optic Object and Reference Beams.

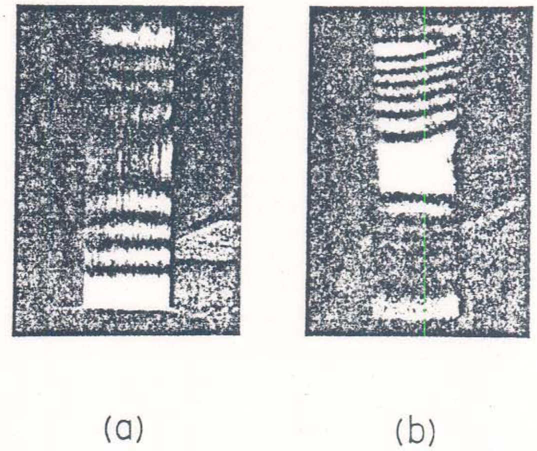

Figure 2. Time Averaged Holo-Interferograms for a Vibrating Cantilever Beam Recorded (a) Directly and (b) Through a Coherent Fiber Optic Bundle.

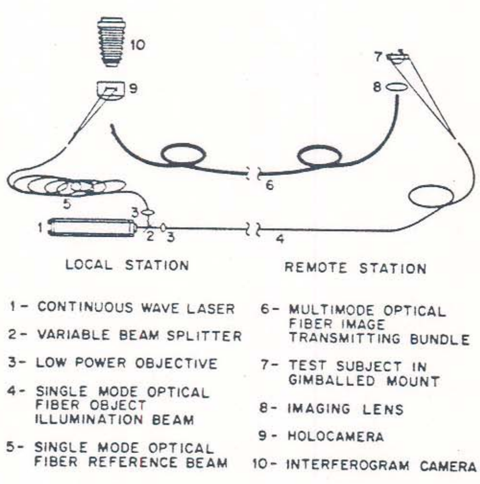

Figure 3. Schematic Diagram of a Holographic System for Recording Fraunhofer Holo-Interferograms through a Coherent Fiber Optic Bundle.

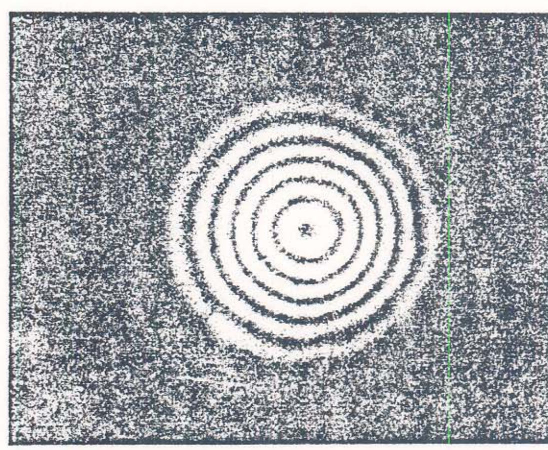

Figure 4. Reconstruction of a Holo-Interferogram of a Centrally Loaded Disk Recorded in Real-Time Through a Coherent Fiber Optic Bundle.

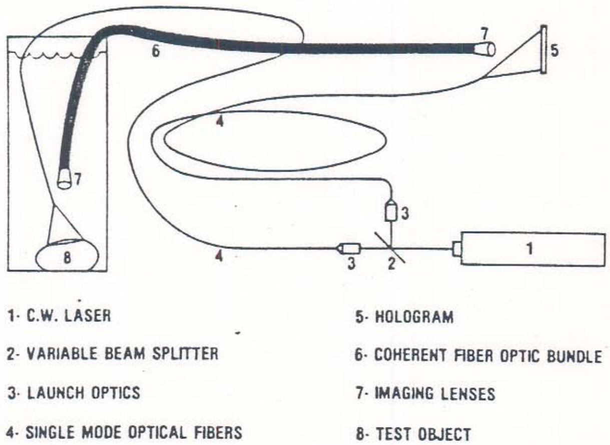

Figure 5. Schematic of a Fiber Optic System for Recording Holograms of Immersed Subjects.

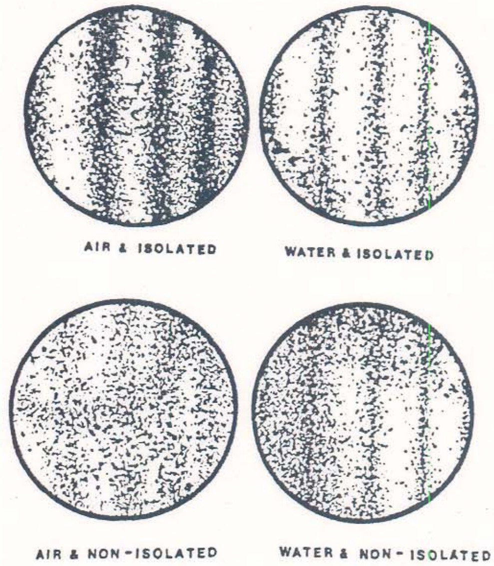

Figure 6. Reconstructions of Four Holo-Interferograms Showing the Deformation Fringe Pattern for a Cantilever Beam as Recorded Through a Coherent Fiber Optic Bundle, both in Air and Under Water, and on and off a Vibration Isolated Bench.

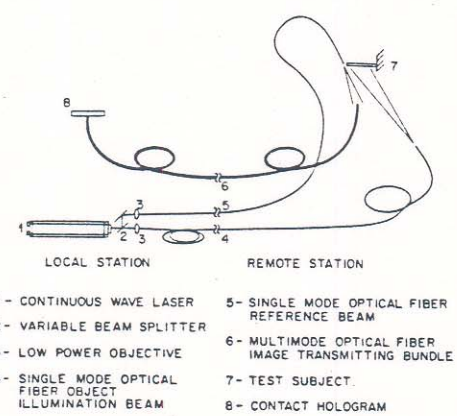

Figure 7. Schematic of a Fiber Optic System for Remote Ultra-Low Spatial Frequency (ULF) Holography.

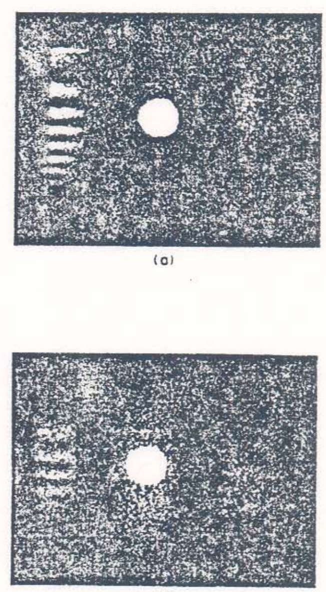

Figure 8. Reconstructions of ULF Holo-Interferograms of an End Loaded Cantilever Beam Recorded (a) Directly and (b) Through a Coherent Fiber Optic Bundle.