Holography

Commemorating the 90th Anniversary of the Birth of Dennis Gabor

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The uses of fiber optics to enhance and extend the
capabilities of holographic interferometry[1]

by

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ABSTRACT

The advent of low-loss optical fibers in the early 1970s was a major event in the field of communications. Since then, material and fabrication technologies have progressed rapidly and, non-communications applications for fiber optics have become widespread. For example, optical-fiber components are routinely used in holography and holo-interferometry to realize significant improvements in stability, flexibility and accessibility.

This paper reviews the history of the application of individual single- and multimode fiber-optic components to the manipulation of both object and reference beams, and the use of multimode fiber-optic image bundles for object-to-hologram wavefront transmission. The advantages and disadvantages of singlemode versus multimode fiber-optic components will be discussed, and techniques for improving the stability of multimode fiber-optic components will be presented. Tests conducted using singlemode fibers (SMF) as stable illuminators and a singlemode image transmitting (SIT) fiber-optic component for wavefront transmission between the object and the hologram will be described. Other techniques which rely on holographic/fiber optic recordings, such as radial metrology and real time moire interferometry, will also be discussed.

1. INTRODUCTION

Over the last decade, the work of various investigators has demonstrated the practical uses of fiber-optic elements for holography and holographic interferometry.[1]-[71] Experience has established that individual singlemode optical fibers provide convenient, highly stable illuminators for holographic interferometry,[7,16,22] while coherent fiber-optic bundles may be used to transmit holographic images[3,12,16] for recording and analysis at locations remote from the actual test object. Moreover, fiber-optic bundles and large diameter individual multimode optical fibers may be used as flexible illuminators for pulsed laser holography.[13,17,27,34] Individual optical fibers and coherent fiber-optic bundles may be used in both local and remote holographic systems, including double exposure,[11,12,14,16] time average[28] and real-time[29,31,32] holographic interferometry. Special servo-driven phase compensation systems have also been developed to enhance the superior stability of singlemode optical fiber illumination by offsetting the effects of strain or temperature induced changes in phase.[22,32] Procedures for recording both image plane ("white light") and Fraunhofer holograms through fiber-optics have now been developed, as well as a method for greatly suppressing the inherent instability of commercially available multimode fiber-optic image bundles through the use of an "ultra low (spatial) frequency" or ULF holographic technique.[20,24] Singlemode image transmitting (SIT) fiber-optic components have been used to transmit a coherent image (wavefront) from object to hologram in an all singlemode system appropriate for remote applications.[70] Singlemode fibers have also found applications in speckle metrology[61,62,64,65] and moire interferometry[69].

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2. FIBER-OPTICS

In the simplest case, an optical fiber consists of a solid uniform core of highly transparent material whose index of refraction, n_{Co}, is slightly higher than the index of refraction, n_{Cl}, of the cladding which surrounds it such that $n_{Cl} = n_{Co}(1-\Delta)$. (Usually the cladding itself is surrounded by an outer protective but lossy sheath.) In this "step-index" design a light ray traveling in the core will be guided so long as its incidence angle, θ, to the core-cladding interface is sufficiently shallow. For most practical fibers the index difference, Δ, is very small, varying between a few tenths of a percent to a few percent. In such cases a critical incidence angle (defined by Snell's law) may be taken as $(2\Delta)^{1/2}$. This means that all meridional rays propagating at $\theta \le (2\Delta)^{1/2}$ will be totally internally reflected every time they intersect the core-cladding interface, and thus be guided, without loss, along a zig-zag path down the core. On the other hand, those meridional rays propagating at angles larger than $(2\Delta)^{1/2}$ will be at least partially refracted out into the cladding. Consequently, such rays are successively attenuated at each reflection and soon "disappear." Of course, light rays are not restricted to meridional paths (in a single plane) and many guided rays follow spiral paths down the fiber core. Similar arguments may be applied to fibers with more complex index distributions. In these fibers the guided rays follow curved paths as they are refracted back and forth (perhaps spiraling) down the fiber core. Again, rays propagating at too great an angle will be lost, while those at shallower angles will be guided.

All fibers exhibit a critical or maximum angle limiting the propagation directions of guided rays (waves), regardless of the index configuration. Translated into external angles for guidable rays entering or leaving the flat, squared off end of such a fiber, this critical angle defines its numerical aperture, NA. In air (a medium of $n \approx 1$) $NA = n_{Co}(2\Delta)^{1/2}$. For a typical fiber with a Δ of around 0.01 the NA would be around 0.21, which means that it would "accept" or "radiate" light rays propagating within a 24° core angle. Actually, not every wavefront whose propagation direction lies within the NA will be guided. In a rigorous analysis of light propagation the wave (rather than ray) character of light must also be considered. This involves solving Maxwell's equations and yields a discrete family of guided wavefronts or modes whose number may be estimated from the theoretical relationship given by Marcatili;[72]

$$N = \frac{g\Delta}{2+g} \left[\frac{2\pi n_{Co}a}{\lambda} \right]^2 \qquad (1)$$

derived for a fiber whose core index varies in the radial direction according to the power law

$$n = n_{Co}[1 - \Delta(r/a)^g]. \qquad (2)$$

Here a is the core diameter, r the distance from the fiber center and g the profile parameter. (Note that a step index fiber is described by $g = \infty$, while a low dispersion "square-law" or parabolic graded index fiber is described by $g = 2$.) Theoretically, it is possible to design a fiber to guide any number of modes as desired, including just one, by the proper choice of a, g and Δ for a given wavelength. (Actually at $N = 1$ two modes of orthogonal polarization will propagate along the fiber.) In recent years the development of processes for the manufacture of practical, low loss optical fiber with the desired characteristics for telecommunications has been the focus of a highly successful technological effort by many parties (see Miller and Chynoweth,[72] or Arnaud[73]). In telecommunications applications the choice between so called singlemode and multimode optical fiber is, in a sense, a simple choice between one signal path and many. Since the many paths of a multimode fiber mean many differing travel times, the inevitable modal dispersion means a significant loss of bandwidth when compared with singlemode fiber. Consequently, the superior performance of singlemode fiber systems must be weighed against their greater cost. In these times of rapidly falling cost, singlemode systems are becoming the predominant choice. When it comes to coherent metrology, our present topic, somewhat different considerations also lead to the identification of a very great advantage in using singlemode fiber optics wherever possible, as will be explained.

3. SINGLE VERSUS MULTIMODE FIBER-OPTICS

When a single multimode optical fiber is excited by coherent light from a laser the far field radiation emitted at the

output end, when polished flat and square to the fiber axis, appears as a rather coarse random speckle pattern, hardly a desirable field with which to illuminate a holographic or laser speckle test subject. Furthermore, it will be noticed that even if the input and output ends of the multimode fiber "illuminator" are held firmly, a small movement of the fiber anywhere along its length generates a significant revision of this speckle pattern. This occurs because small changes in the bending radius induce significant changes in the modal propagation pattern. Unfortunately, such changes mean a significant loss of correlation. Consequently, unless they are fixed rigidly all along their length, such multimode fiber components are inherently unstable in the presence of even small motions - a severe problem when considering holographic applications for example.

Of course, the coarse far-field emission pattern can be made much finer by increasing the core diameter, but the motion related modal instability would remain. However, if a step-index optical fiber of sufficiently small core diameter and index difference (say around 7 µm at a step-index Δ of perhaps 0.0017) were chosen, its operation would be singlemode in the visible light range and the far field emission patterns would look like the output from a classical "objective and pinhole" spatial filter normally employed in CW holography. In a way, such a singlemode fiber (SMF) may be thought of as an extremely long, flexible 7µ pin hole capable of delivering an intense beam of filtered coherent illumination anywhere desired -- that is, as an excellent coherent illuminator! Furthermore, because it is singlemode, it has the advantage of being relatively stable -- so long as its ends are fixed, mechanical disturbances along its length have little or no effect on the stability of the illumination.

4. IMAGING THROUGH FIBER OPTICS

Of course, illuminating the test subject with a SMF accomplishes only a part of the task of accessing a remote object for optical measurement. In applications to holographic interferometry (including remote holography) it may be necessary to return an "image" of some sort from the illuminated remote test surface to a local test station for recording as a hologram and analysis. As it happens, individual single core SMFs do not readily transmit images - at least not as analog signals. However, flexible coherent bundles of multimode optical fiber (hereafter called multimode bundles or MMBs) are commercially available with the resolution and size required for high quality remote imaging with coherent light and, accepting their limitations on stability, such MMBs have been applied to all such holographic applications to date. With the fabrication of singlemode image transmitting fiber-optic components or SIT fibers, it is now possible to evaluate their performance and draw a meaningful comparison with MMBs for such critical applications as will be described.

5. HOLOGRAPHIC INTERFEROMETRY

Holography utilizes the optical interference which occurs between two intersecting beams of mutually coherent light to generate and record, in some amplitude sensing medium (e.g. a photographic emulsion), a complex diffraction pattern. If recorded correctly, this pattern, or "hologram" as it is commonly called, will have encoded within it all the information required to reconstruct either of the two original beams of coherent light (used to generate the interference pattern) whenever it is illuminated by the other. In other words, a hologram provides a practical means of reproducing an original coherent wavefront, complete in terms of both amplitude and phase, at any time desired. Furthermore, this capacity to record and accurately reconstruct a field of phase information holographically provides the means of doing optical interferometry on arbitrary objects. Thus, holo-interferometry involves interfering coherent wavefronts recorded at different times and observing the development of interference fringes. These fringes are associated with the spatial distribution of phase differences between the two wavefronts, and may be uniquely related to the differences in optical path length between these wavefronts which arise because of changes imposed on the test subject, so long as they are the only changes affecting phase.

In a classical off-axis holographic system coherent light from a laser is divided by a beam splitter to provide one beam for the illumination of the test subject (called, naturally, the "illumination" beam) and another beam of illumination of the hologram (called the "reference" beam). The test subject and the hologram are arranged so that coherent light reflected from or transmitted through the test subject reaches the holograms as well. This is referred to as the "object" beam or "object" wavefront, and its combination with the reference beam produces the complex standing wave interference pattern that is to be recorded on the hologram. Subsequent reillumination of the processed hologram by the reference beam will generate, by diffraction, an exact optical replica of the original object

wavefront.

In addition to the need to achieve an appropriate intensity balance between the object wavefront and the reference beam so as to assure an appropriately modulated hologram, the holographer must consider a variety of additional factors affecting hologram quality. Naturally, when the object and reference beams meet at the hologram the two wavefronts must be mutually coherent or no standing wave interference patterns will be formed. As it happens, the coherent length of the illumination from a laser is not infinite, but may in fact be quite limited. Consequently, when using such a coherent light source, if the optical path length of the reference beam differs from the total optical path length of the illumination plus object beam by more than the distance when they reach the hologram plane, there will be no interference and *no hologram will be recorded*! In conventional (non-fiber-optic) systems this need to match path lengths within a limited coherence length often leads to reference beams which must be folded back and forth on the optical bench in order to achieve the necessary optical path length. Moreover, even if the coherence conditions are satisfied, small motions anywhere in the system of optical components used to manipulate any of the beams can destroy the hologram completely if they induce a shift of as little as half a wavelength in the standing wave interference pattern during recording. Consequently, such holographic systems are generally mounted on sophisticated vibration isolated tables with numerous heavy rigid mounts for an often complex system of mirrors, prisms and lenses used to shape and manipulate the light. Finally, long optical paths through air are frequently subjected to time varying phase shifts resulting from the integrated effects of thermal air currents which can also have a deleterious influence on stability.

6. LOCAL HOLOGRAPHIC SYSTEMS WITH FIBER-OPTICS

While no panacea, the use of fiber-optic components to transmit and manipulate the object illumination and/or reference beams can be very helpful in dealing with some of the problems discussed above. Figure 1 shows a diagram of a holographic system in which the use of SMF illumination for both beams provides a facility whose realization on the bench rivals a schematic in simplicity, which is rarely the case with non-fiber-optic systems. Moreover, in addition to the immediate improvement in simplicity and flexibility, the use of a fiber-optic reference beam makes it easy to match optical path lengths simply by preparing SMFs of appropriate length. So long as (1) the launch optics and bidirectional coupler (or, alternately, a beam splitter and pair of launch optics) are rigidly affixed to the laser or optical bench, and (2) the two fiber outputs, the test subject and the hologram are firmly maintained in their relative positions; vibrations or displacements along the fiber paths will have little or no effect on the operation of the holographic system. Figure 2 shows

1. LASER
2. SHUTTER
3. LAUNCH OPTICS
4. BI-DIRECTIONAL COUPLER
5. REFERENCE BEAM OPTICAL FIBER
6. OPTICAL PATH LENGTH MATCHING LOOP
7. HOLOGRAM
8. OBJECT ILLUMINATION OPTICAL FIBER
9. TEST OBJECT

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

doubly exposed holographic interferograms recorded using just such a local system during a study[29] of the thermally induced warping of multilayer printed circuit boards with different stackup asymmetries. This study was made using a holo-interferometer with the illumination and reference beam SMFs fixed only at their ends and otherwise "free in the breeze".[18] (Had multimode fibers been used in place of the SMF illuminators, the vibration in the table would have required providing either total vibration isolation or rigid support all along their lengths to assure the stability needed to do double exposure holo-interferometry.)

Recently Jones et al[22,25,32] described a two SMF holography system in which an etched directional coupler was used to amplitude divide an SMF guided beam into the reference and object beam fibers, for which they claimed improved mechanical stability and convenience in comparison with a beam splitter plus two launch optics system or a fixed ratio bidirectional coupler and variable attenuator system. They also described an electronic servo-system to assure
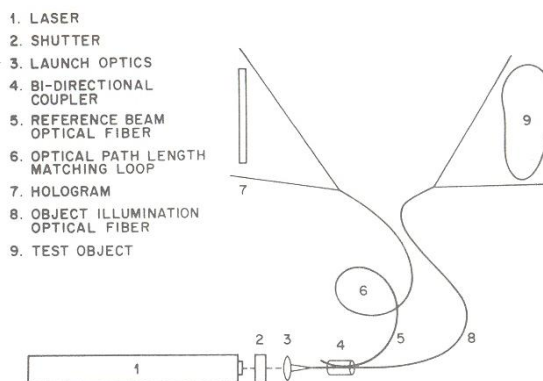
the thermal stability required for very long exposures with thermally sensitive fibers. Such singlemode fiber-optic local systems can readily by used for double exposure, time average, and real-time holographic interferometry.

7. REMOTE HOLOGRAPHIC SYSTEMS WITH FIBER-OPTICS

In the preceding examples the object wavefront was transmitted by direct line-of-sight from the test subject to the hologram plane. However, many situations arise in which the test subject may not be so conveniently located, and for which it would be advantageous to use flexible fiber-optics to both (1) illuminate the obscured or remote object and to (2) transmit the resulting object wavefront back to the hologram plane for recording and observation. In such a situation an SMF illuminator can be used in conjunction with a multimode imaging bundle (MMB) to provide a "remote" holographic capability. Figure 3 shows a schematic diagram of the type of mixed mode fiber optic holographic system that would be used to realize this concept. Lenses are used to image the test subject onto one end of the imaging bundle and from the other end of the imaging bundle onto the hologram, thereby creating an image plane holographic system. (Image plane holograms may be reconstructed with incoherent or "white" light. If the MMB output lens is removed the resulting holograms are Fraunhofer type and not "image plane" and, consequently, will require coherent light for proper reconstruction.) Figure 4 shows a white light reconstruction of a double exposed image plane holo-interferogram recorded using a similar system.[16] The test subject was a clamped circular plate subjected to a central displacement towards the viewer so as to create a pattern of circular interference fringes. Each fringe represents a change in displacement of approximately half the wavelength of light. The pattern of individual 12μ diameter fibers in the bundle can be seen clearly in the reconstruction, which is typical of well focused reconstructions of remote image plane holograms. Because these experiments were carried out on a vibration shielded optical bench and because care was taken to assure that the MMB was unperturbed, the stability limitations of such a multimode component were of little consequence. However, it would be desirable to be able to combine the object illuminating and imaging fiber-optics into a kind of holographic probe capable of functioning in more active environments. In this situation the MMB can be expected to experience significant mechanical disturbances and would probably be of limited practical
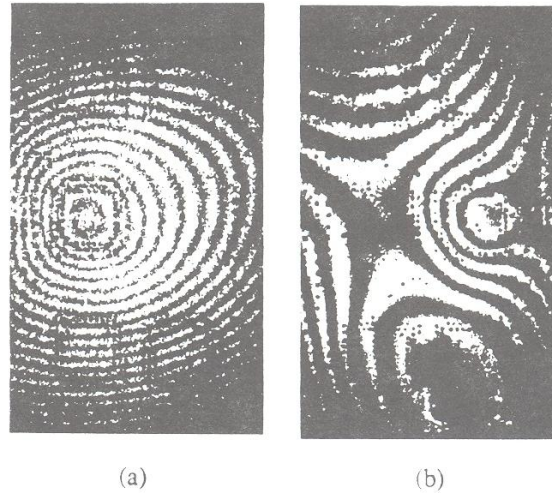

(a)   (b)

Figure 2. Thermally Induced Displacement Responses of Microelectronic Modules[29] due to 0.375 watts of Power Dissipation with (a) Large and (b) Small PTH Clearance Holes.
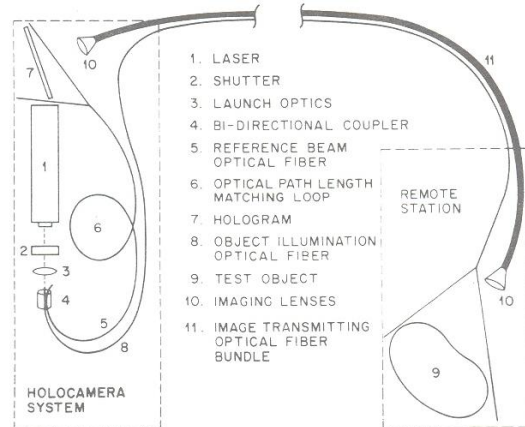

1. LASER
2. SHUTTER
3. LAUNCH OPTICS
4. BI-DIRECTIONAL COUPLER
5. REFERENCE BEAM OPTICAL FIBER
6. OPTICAL PATH LENGTH MATCHING LOOP
7. HOLOGRAM
8. OBJECT ILLUMINATION OPTICAL FIBER
9. TEST OBJECT
10. IMAGING LENSES
11. IMAGE TRANSMITTING OPTICAL FIBER BUNDLE

REMOTE STATION

HOLOCAMERA SYSTEM

Figure 3. Schematic Diagram of a Holographic System for Recording Image Plane Holo-Interferograms of a Test Object at a Remote Station through a Coherent Multimode Fiber-Optic Bundle (MMB).

use.

As an example of a potential "practical", if unique application, a mixed mode fiber optic holographic system with a 4 mm diameter MMB several meters long was used to evaluate performance both in air and *under water*. In this demonstration[19] the test subject was a simple end loaded cantilever beam mounted, along with the necessary fiber optics for illumination and image transmission, in a movable test fixture. This fixture could be mounted either in the open with the rest of the system, or submerged in a tank of water. Double exposed image plane holo-interferograms recorded and reconstructed for both cases are shown in Figure 5. As might be expected, the best interference fringes were obtained in air, but those obtained under water were almost as good. Had no fiber optics been available to pierce the surface of the water, surface motion would probably have made it very difficult to obtain any visible fringes, even on a vibration isolated optical bench. Furthermore, any sort of flexing or vibration of the MMB during the recording process in any of these tests would have completely destroyed the hologram.
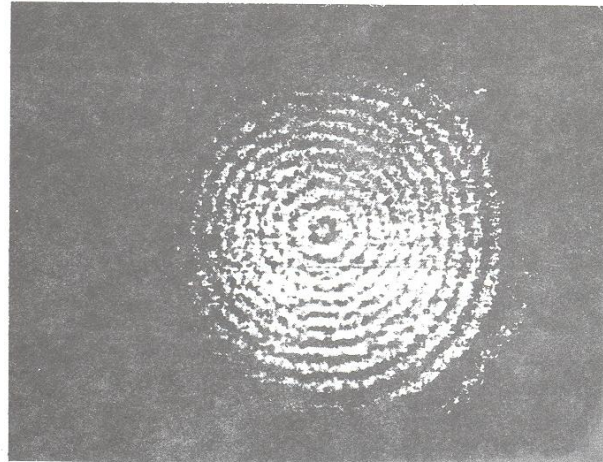

Figure 4. White-Light Reconstruction of an Image Plane Holo-Interferogram[16] of a Centrally Loaded Disk Recorded Through a Coherent Multimode Fiber-Optic Bundle (MMB).

Of course, one way of suppressing this problem would be to shorten the hologram recording time so as to effectively "stop" the motion by using a pulsed laser as an illumination source, as demonstrated by several investigators.[12,13,17,34] While this usually works quite well for holography, the pulsed laser approach to resolving the problem of MMB instability frequently will not work in remote applications to real-time or double exposure holo-interferometry unless the same stringent stability conditions are met between exposures that would apply using a CW system. Consequently, it can be seen that while a flexible multimode fiber optic "probe" with pulsed ruby laser excitation works very well for recording "remote" single exposure holograms, it probably won't work nearly as well (if at all) for interferometry because, if the system experiences any motion during the test, the images won't correlate well enough to produce usable interference fringes. Of course, it would be effective in applications to dynamic problems
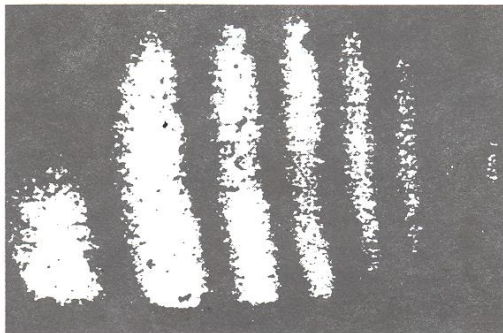
(a)
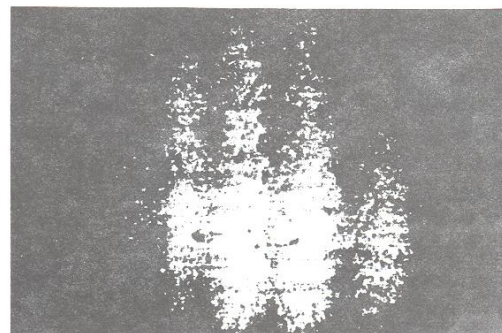
(b)

Figure 5. Reconstructions of Two Holo-Interferograms[19] Showing the Deformation Fringe Patterns for a Cantilever Beam as Recorded Through a MMB, both (a) in Air and (b) Under Water.

where the events being monitored take place on a faster time scale than that of any likely disturbances of the MMB between exposures, including thermal effects arising from the interactions of the light pulses with the optical fiber illuminators.

8. ULTRA LOW FREQUENCY HOLOGRAPHY AND HOLO-INTERFEROMETRY

Another approach to achieving the required stability with flexible MMBs for remote holography is 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 phase information and is, consequently, rather sensitive to the effects of any disturbance that effects the modal propagation characteristics of the MMB. However, transmitting the image of a hologram requires transmitting a complex interference fringe pattern whose spatial frequency would normally lie well beyond the capabilities of all currently available MMBs. This means that the successful use of a flexible (and possibly moving) MMB to transmit a hologram requires generating a very low frequency interference fringe pattern. This in turn means that both the illumination and reference beams must be transmitted to the "remote" location and that the reference and object image beams must intersect at a very small angle wherever they are to be sampled by the MMB. The schematic shown in Figure 6 illustrates such an arrangement in which two SMFs of appropriate length would be used to carry the coherent illumination and reference beams to the remote subject and an MMB of exceptionally large diameter and high resolution would be used to return the ultra low frequency interference pattern to the holocamera system. Figure 7 shows reconstructions of ULF holograms of the letter "H" recorded directly and through an MMB of 10 mm diameter and around 33 lines/mm resolution in an original study[20] demonstrating the ULF technique. In this demonstration the hologram "image" was contact printed directly onto a high resolution film plate to produce a ULF hologram of 10 mm diameter. Although there is an unavoidable loss of resolution and contrast associated with transmission through the MMB, in both cases the results were quite good. In a subsequent study,[24] ULF holo-interferometry was successfully applied to the measurement of deflections in a cantilever beam. Except at the ends, motion isolation of the fiber-optic components was not required in any of these demonstrations. In other words, the ULF technique confers motion insensitivity on the MMB as a hologram transmitter functionally comparable to the motion insensitivity of the SMFs used as illuminators. Consequently, not only can this ULF technique be used to record remote holograms in
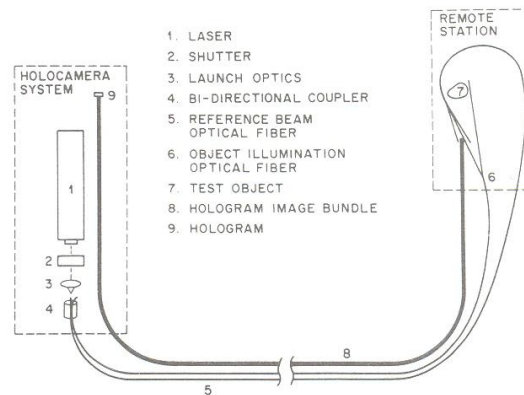
1. LASER
2. SHUTTER
3. LAUNCH OPTICS
4. BI-DIRECTIONAL COUPLER
5. REFERENCE BEAM OPTICAL FIBER
6. OBJECT ILLUMINATION OPTICAL FIBER
7. TEST OBJECT
8. HOLOGRAM IMAGE BUNDLE
9. HOLOGRAM

Figure 6. Schematic of a System Using a Coherent Multimode Fiber Optic Bundle (MMB) for Remote Holographic Interferometry by the Ultra-Low (Spatial) Frequency or ULF Technique.
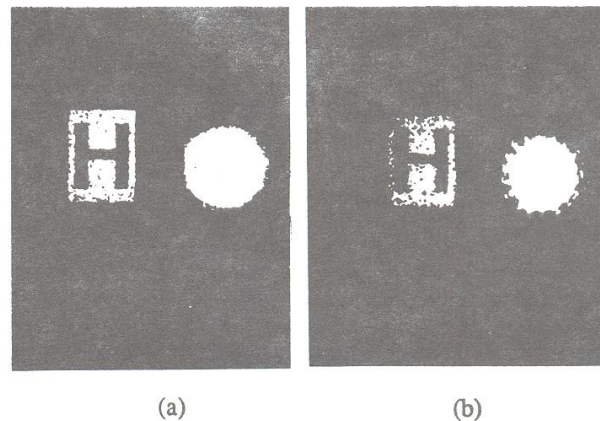
(a)   (b)

Figure 7. Reconstructions of ULF Holograms[20] of the Letter "H" Recorded (a) Directly and (b) Through a Coherent Multimode Fiber-Optic Bundle (MMB).

the presence of significant motion along the fiber-optics, but unlike the pulsed ruby laser fiber-optic technique it can also be used to do "practical" remote holographic interferometry.[24]

Unfortunately, there are serious limitations to this technique in so far as a holographic probe is concerned. The need for a low angle reference beam configuration creates a geometrical complexity that makes design of a suitable probe head awkward to say the least. Moreover, the restriction on hologram bandwidth imposed by the restricted resolution of the MMB is extremely limiting. This component functions as a low pass filter, effectively eliminating the higher frequency fringes in the standing wave interference pattern, and thereby restricting the range of possible propagation directions in any complex wavefront to be diffracted by a hologram recorded at the MMB output. This, in turn, limits both the size and complexity of any test subject to be recorded holographically, as well as the range and complexity of any deformation field to be measured interferometrically. Increases in either the area of illumination (subject size) or beam deflection (measurement range) act to increase the complexity of the standing wave interference pattern that must be transmitted. With any such increase there is an associated increase in the proportion of higher frequency components which will be cut off by the MMB and consequently cannot contribute to the formation of the hologram. Furthermore, the combination of a relatively small hologram (which of itself reduces the information available to reconstruct the image) with a large reconstructed image viewing distance (necessitated by the small reference-to-object beam angle) will result in the development of significant objective speckle noise in the reconstructed image, with an associated loss of resolution. This speckle noise is the result of a kind of self interference associated with coherent light, and is commonly manifest in the granular appearance of any diffusely reflecting surface when it is illuminated with such light.

The use of a larger diameter (D > 10 mm) MMB would certainly reduce this speckle problem and improve the signal to noise ratio. Unfortunately, such a bulky component would also be extremely expensive. However, the same result might be achieved through the use of a coherent array of far less expensive MMBs of smaller diameter. Indeed, an effectively optimized fiber-optic ULF holo-interferometric probe system would require both the largest practical MMB/hologram areas and significantly improved MMB resolution to reduce the limiting effects of restricted bandwidth. So far, no one has found this to be worth doing, for obvious reasons.

9. EXPERIMENTS WITH SINGLEMODE IMAGE TRANSMITTING OPTICAL FIBERS

Considering the significant improvements achieved using individual singlemode optical fibers for object and reference beam illuminators, a study was recently initiated to evaluate the capabilities of a singlemode component for the transmission of the object to hologram wavefront.[70] This study used a singlemode image transmitting (SIT) fiber of 600 cm length and only 1.08 mm diameter with a minimum bend radius of less than 200 mm. In order to transmit images it was fabricated with 20,000 light guiding cores of 2.16 μm diameter and a 5.4 μm cladding diameter in a common glass matrix. This provided an image of 20,000 pixels and a 600 nm singlemode cut-off wavelength.

In the experiments themselves, image plane holograms of a tiltable disk were recorded with the subject SIT fiber used to transmit the wavefront from the object to the hologram instead of an MMB. A thermoplastic holocamera was used to record the holograms so that real-time fringe patterns could readily be observed and photographed. For maximum operating flexibility, instead of using a fixed ratio bidirectional coupler and attenuators, the output from an Argon-Ion laser (tuned to 514 nm and operating at 150 mw) was divided by a variable density beamsplitter. The object beam illuminated the central region of a painted (white) aluminum disk which was mounted in a frame that permitted controlled rotations about two orthogonal transverse axes through its' center. Using this system, the disk was oriented so that the normal to its' surface bisected the angle between the object illumination and the SIT fiber. This provided a 35 mm diameter field of view of the disk which was imaged through a 33 mm f/1 ERFL lens onto the input end of the SIT fiber by a 35 mm f/1.2 Nikon lens.

In order to evaluate the stability of the SIT fiber when subjected to mechanical displacements along its length, the SIT fiber was mounted rigidly at either end but left slack in between. A translation stage located at the mid-point of the SIT fiber provided a convenient means of imposing quantified displacements as desired. The optical signal transmitted through the SIT fiber was focused onto the hologram plane of a thermoplastic holocamera by a 10 mm objective positioned to yield a 25.4 mm diameter image. The singlemode reference fiber was angled at 25 degrees to the SIT fiber and collimated with a medium (200 mm) focal length lens.
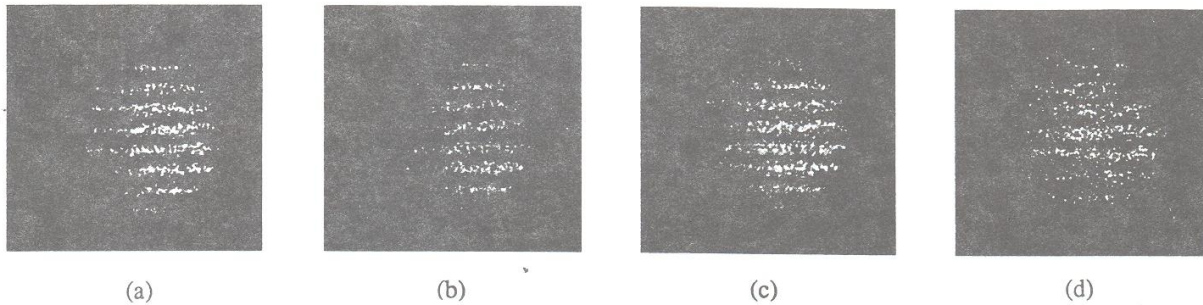
(a)   (b)   (c)   (d)

Figure 8. Reconstructions of a Tilted Disk Recorded Through a Singlemode Image Transmitting (SIT) Optical Fiber with the Midpoint Displaced (a) 0.00 mm (b) 0.625 mm (c) 1.27 mm and (d) 2.54 mm.

After recording a reference hologram, the reference and object beam intensities were adjusted to optimize the contrast. A real time fringe pattern shown in Figure 8a was introduced by rotating the disk 0.003 degrees about the vertical axis through its' center. Such fringe patterns, and all subsequent holo-interferogram patterns, were then recorded on polaroid film through a Nikon 55 mm macro lens. Using the translation stage, the SIT fiber was displaced almost 4 mm before the fringe visibility became significantly degraded, Figures 8b, c, and d. This represents a revolutionary improvement in stability and resolution over that of any equivalent multimode image bundle, which will completely decorrelate when exposed to the slightest disturbance. Using such a component, it is quite possible to consider an SIT fiber based-optic probe system for remote holo-interferometric sensing with practical operating characteristics.

On the other hand, the subject SIT fiber by no means matched either the flexibility or the motion insensitivity of the individual SMFs used as illuminators, which under appropriate circumstances can be displaced several centimeters without serious decorrelation. Several factors may contributed to this observed difference. First, uncompensated phase differences may arise because of variations in bending induced axial strain from core to core across the SIT fiber. However, in the subject SIT fiber such bending strain would vary linearly across the field in a direction transverse to the bending axis, and no such behavior was observed. However, there are at least two other possibilities. First, depending on the difference between the nominal cut-off wavelength and the operating wavelength, there may be some multimode behavior. This can easily be managed by careful matching of the specifications for SIT fiber fabrication to the desired operating laser wavelength. Second, because the multiple cores on the subject SIT fiber share a common cladding matrix, the more likely explanation would be the introduction of cross-talk associated with increasing bending losses. If this is the case, the use of an ultra high loss cladding should substantially suppress this effect and further improve the performance of such SIT fiber components for applications to holo-interferometric probe systems.

10. FURTHER EXAMPLES OF HOLOGRAPHIC/FIBER OPTIC SYSTEMS

In addition to the more conventional holographic systems mentioned above, several new techniques, which rely on holographic/fiber optic recordings, are currently under development. High frequency moire interferometry, for example, is a highly sensitive full-field optical method useful for measurement of surface displacement. The technique requires that a reflective high-frequency phase-type grating be transferred from a mold to the surface of the specimen. Figure 9 illustrates that holographic techniques can be used to store an initial carrier pattern for real-time analysis in the most general case.[69] Fiber-optic components have been incorporated into the experimental setup to provide greater flexibility and potential optical access to remote test locations. In this technique, real-time holo-interferometric fringes, recorded on a thermoplastic holocamera, are eliminated by reconstructing the carrier pattern (and each of the initial holograms) using horizontally polarized light (produced by rotating the half-wave plate and

polarizer in the reference beam). In this case, the vertically polarized object beam and the horizontally polarized reference beam produce no interference and no real-time holo-interferometric fringes. However, the initial moire interferometric carrier is still reconstructed holographically. This pattern may then be superimposed on the deformed carrier, which depends only upon the interference between the two object wavefronts diffracted from the specimen in its loaded condition.

The advantages of fiber optics have also been exploited in the design and development of holoendoscopes which rely on a panoramic annular lens (PAL).[71] The PAL maps a cylindrical cavity onto a flat surface by a technique called flat cylinder perspective (FCP). Figure 10, for example, illustrates one of many possible configurations currently under consideration. In this example, a holoendoscope is shown inserted into a cylindrical cavity. Laser light is launched into a bidirectional fiber coupler (not shown in the figure), and one leg of the coupler, shown in the figure as a singlemode fiber labeled {1}, is incorporated into the device. The diverging beam from the fiber is directed through a projection lens {2}, passes through the central portion of a PAL {3}, and is shaped by a collimating lens {4}. The emerging beam reflects off an appropriately shaped mirror {5} and passes through a transparent window {6} onto the test surface {7}. The image of the illuminated surface is captured through the transparent window {6} by the same PAL used to illuminate the cavity {3} and the virtual image is transferred by the projection lens {2} to a coherent optical fiber bundle {8}. The bundle transmits the image from the holoendoscope to the recording site where the object wavefront is superimposed with the output from the other leg of the coupler.

11. SUMMARY AND CONCLUSIONS

In holographic applications fiber-optic components may be used in many ways. Individual singlemode fibers (SMFs) 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, SMFs 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 the holographic and even holo-interferometric capabilities of great potential value in experimental mechanics. The need to transmit an image required that this third flexible fiber-optic link be a coherent fiber optic image bundle. Unfortunately, bundles constructed from thousands of coherently arrayed fine multimode optical fibers are significantly less stable (for
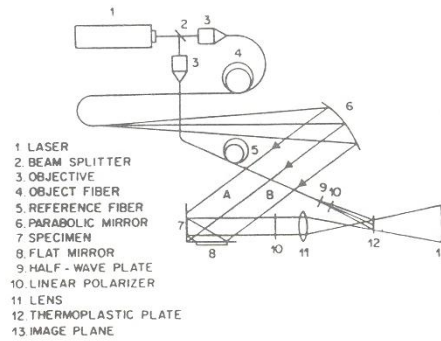
1. LASER
2. BEAM SPLITTER
3. OBJECTIVE
4. OBJECT FIBER
5. REFERENCE FIBER
6. PARABOLIC MIRROR
7. SPECIMEN
8. FLAT MIRROR
9. HALF - WAVE PLATE
10. LINEAR POLARIZER
11. LENS
12. THERMOPLASTIC PLATE
13. IMAGE PLANE

Figure 9. Schematic diagram showing an experimental setup for recording real-time moire interferograms.[64]

1. ILLUMINATING FIBER
2. PROJECTION LENS
3. PANORAMIC DOUGHNUT LENS
4. COLLIMATING LENS WITH MASK
5. CONICAL MIRROR
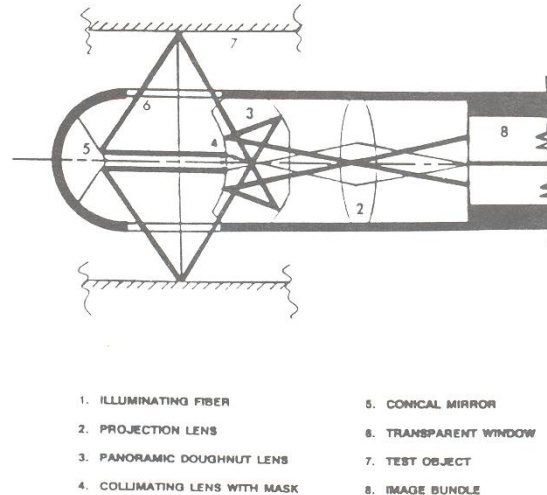6. TRANSPARENT WINDOW
7. TEST OBJECT
8. IMAGE BUNDLE

Figure 10. One of many configurations for a holoendoscope which incorporates a panoramic annular lens (PAL).

holographic applications) than are the SMFs used for illumination. This means that, with any combined single and multimode fiber-optic holography system wherein the MMB must transmit both amplitude and phase information, considerable care must be taken to secure the full length of the MMB against the deleterious effects of mechanical movement or vibration. Otherwise, such motions produce changes in the MMBs 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 a 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 MMB disturbances. On the other hand, mixed mode holographic systems which do not entail the transmission of phase information via the MMB, such as remotely generated holograms of ultra-low spatial frequency, are quite stable and effective for both holography and holographic interferometry. However, a true ULF probe system would be geometrically challenging and require an MMB 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. The use of a flexible singlemode image transmitting optical fiber of slightly more than 1 mm diameter has been explored. Results of real-time holo-interferometry studies indicate a degree of stability significantly better than can be obtained with the multimode bundles used for object-to-hologram wavefront transmission in all previous experiments in fiber-optic holo-interferometry.

12. ACKNOWLEDGEMENTS

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