Characterization, Production and Reconstruction of Substrate Guided Wave Holointerferograms

by J.A. Gilbert and Q. Huang

ABSTRACT—Substrate guided wave (SGW) holograms are recorded and reconstructed using light waves guided through an optical substrate. The recording geometries for producing transmission and reflection SGW holograms are discussed. Practical guidelines are presented for recording and reconstructing interferograms suitable for nondestructive testing.

KEY WORDS—holography, interferometry, nondestructive testing.

Introduction

Substrate guided wave (SGW) holography relies on recording and reconstructing holographic images with light waves guided by an optical substrate. Figure 1, for example, shows how an object wavefront can be holographically recorded using a reference wave transmitted thorough a sheet of transparent dielectric material having two surfaces which are locally parallel and optically polished. Light is launched into the substrate by illuminating one edge at a slight angle; the process may be enhanced by appropriately shaping the reference beam and using an input coupler (a prism, a grating or other edge-lighting mechanism). Since the refractive index of the substrate is higher than the index of the surrounding environment, the illuminating wave is confined by total internal reflection and light propagates through the waveguide to the emulsion (silver halide, photopolymer or dichromate gelatin) following coarse zigzag paths. When the hologram is developed and illuminated with a similar guided wave, the previously recorded holographic wavefront is reconstructed.

As compared to conventional holographic recording systems, SGW holographic systems are compact, portable, robust, and relatively easy to align. Since the illuminating beam is encapsulated within the substrate and only the holographic image is diffracted, the hologram can be viewed close to the recording plane without the danger of eye damage associated with the undiffracted light produced during off-axis reconstruction.

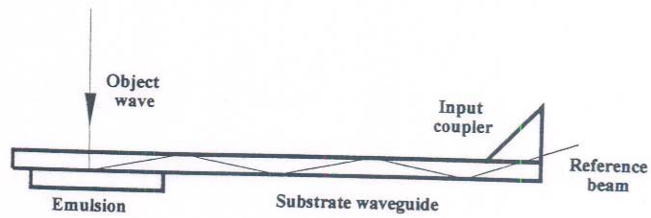

Fig. 1.—Schematic of an SGW hologram recorded with a light wave guided by an optical substrate

Prior Related Research

The original idea for generating SGW holograms can be traced back to 1970 when Lin proposed that holograms could be recorded and reconstructed with light guided through one edge of a holographic plate.[1] In 1976, Suhara, Nishihara and Keyama employed a single-mode waveguide to record and reconstruct two-dimensional holographic images.[2] They caught the attention of the scientific community when they suggested that such elements could form the basis for optical integrated circuits. Bablumyan, Morozov, Putilin and Shermergor expanded on this idea and incorporated waveguide holograms into optical computing, communication, and information storage and processing systems.[3] About the same time, Upatnieks developed SGW holograms for display purposes using an edge-illumination method to produce a reflex-type sight system.[4] A group led by Benton subsequently improved on Upatniek's approach by combining it with a rainbow holographic technique.[5,6] Benton's group used an optical substrate to guide light to the holographic plate as opposed to guiding the wave through the plate itself.

Beginning in the spring of 1990, Caufield and the second author of this paper began investigations on SGW holography and its applications in art and industry. Initial studies, performed with Putilin and Morozov from the former Soviet Union, made use of waveguide holograms generated with white-light illumination.[7] The results obtained from these studies demonstrated that SGW holograms could be employed as illuminators for spatial light modulators and liquid-crystal displays.[8] Several new holographic optical elements were produced including a holographic camera with an SGW holographic beam splitter.[9] The first author joined this research team in 1992 and showed that the SGW holographic technique could be applied to generate double-exposure, real-time and time-average holo-interferograms.[10] The study not only demonstrated that the substrate could be used to isolate the reference wavefront from the environment surrounding the hologram, but that the substrate could be monitored and used as a sensor.

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The following sections characterize SGW holograms and outline the steps required to produce and reconstruct them. The recording geometries for SGW holograms are discussed and compared with those of conventional transmission and reflection holograms. Practical guidelines are presented for producing SGW holograms and an example is given to illustrate how the technique can be applied in experimental stress analysis.

Characterization of SGW Holograms

Holograms may be classified as either transmission or reflection; the distinction is made on the basis of how the hologram is recorded and viewed. Figure 2(a), for example, shows the recording geometry for a conventional transmission hologram in which the object and reference waves impinge upon the same side of the recording material. After the recording material is developed and a hologram is obtained, the image must be reconstructed. This is accomplished by illuminating the hologram with the reference wave. As shown in Fig. 2(b), the reference wave passes through the hologram and produces an image wavefront which emerges from the opposite side of the plate.

The object and the reference waves produce interference within the emulsion and, when the recording material is developed, modulations occur in refractive index. Assuming that the reference and object beams are both plane waves, the modulated index structure is planar and oriented parallel to the angle bisector formed by the propagation vectors corresponding to the object and reference waves. Diffraction occurs in this structure which is shown superimposed on the recording material illustrated in Fig. 2.

In most holographic testing applications, the object is placed on the z axis, so that its propagation vector has a 0-deg incident angle (i.e., normal incidence). If the object is placed off-axis and the object wave is incident upon the emulsion obliquely, the zone in which the reconstructed image appears also moves off-axis. This makes it awkward for an observer to view the image and, in the case of holographic nondestructive testing, complicates displacement analysis.

In conventional holography, the recording beams propagate in free space before entering the recording material; for a transmission hologram, the incident angle for the reference wave can vary from 0 deg to 90 deg with respect to the z axis. According to Snell's law, refraction occurs at the air/emulsion boundary and, for angles different from 0 deg, the incident angle within the emulsion is reduced. Once a recording material has been selected, the range of this angle can be calculated. Consider, for example, silver halide which has an index of refraction equal to 1.63. When the angle of incidence of the reference wave is 90 deg (i.e., grazing incidence), the corresponding incident angle inside the emulsion is

$$\theta_{r,\text{eml}} = \sin^{-1}\left(\frac{n_{\text{air}}}{n_{\text{eml}}} \sin \theta_{r,\text{air}}\right) = \sin^{-1}\left(\frac{1}{1.63} \sin 90 \text{ deg}\right) = 37.84 \text{ deg} \quad (1)$$

Thus, for a transmission hologram, 0 deg $\leq \theta_{r,\text{eml}} \leq$ 37.84 deg.

Figure 3(a), on the other hand, shows the recording geometry for a reflection hologram. As explained previously, the object is usually positioned along the z axis. In contrast to the transmission hologram, the reference and object waves impinge upon the emulsion from opposite sides of the recording material.

Figure 3(b) illustrates that during reconstruction of a reflection hologram, the image wave departs the hologram from the same side from which it is illuminated. Just as in the case of a transmission hologram, refraction at the air/emulsion boundary restricts the angular range of the reference wave inside the recording material itself. For illumination from the right, Snell's law can be expressed for the refraction of the reference wave at the air/emulsion boundary as

$$n_{\text{eml}} \sin (180 \text{ deg} - \theta_{r,\text{eml}}) = n_{\text{air}} \sin (180 \text{ deg} - \theta_{r,\text{air}}) \quad (2)$$

For $\theta_{r,\text{air}}$ = 90 deg, n_{air} = 1.0 and n_{eml} = 1.63 (silver

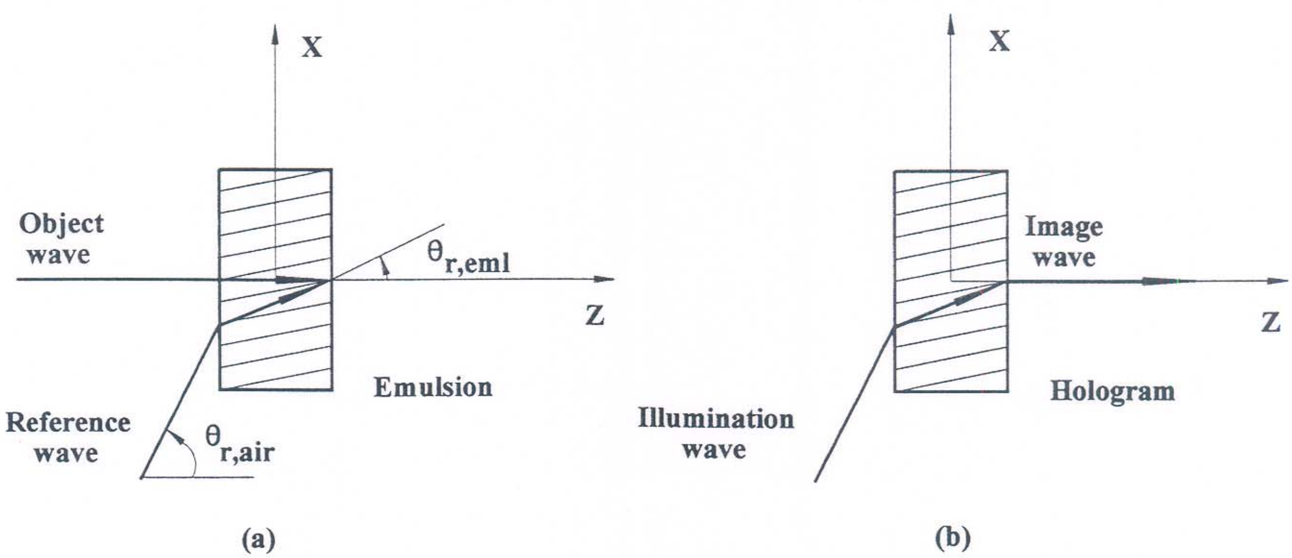

Fig. 2.—Transmission hologram: (a) recording and (b) image reconstruction

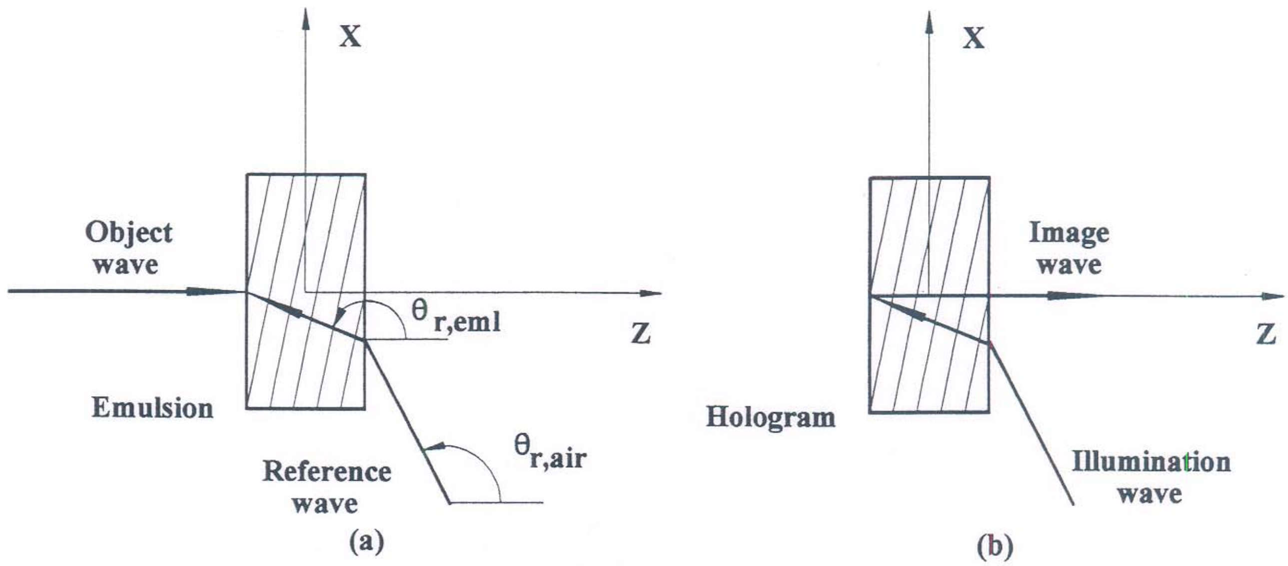

Fig. 3.—Reflection hologram: (a) recording and (b) image reconstruction

halide), the incident angle of the reference wave inside the emulsion is

$$\theta_{r,\text{eml}} = 180 \text{ deg} - \sin^{-1}\left[\frac{n_{\text{air}}}{n_{\text{eml}}} \sin(180 \text{ deg} - \theta_{r,\text{air}})\right]$$
$$= 142.2 \text{ deg} \quad (3)$$

Thus, for a reflection hologram, 142.2 deg $\leq \theta_{r,\text{eml}} \leq$ 180 deg.

The SGW holographic recording geometries shown in Fig. 4 allow access to the zone 37.8 deg $\leq \theta_{r,\text{eml}} \leq$ 142.2 deg which is inaccessible when using the conventional holographic recording geometries described above. The range 37.8 deg $\leq \theta_{r,\text{eml}} <$ 90 deg, Fig. 4(a), corresponds to an SGW transmission hologram; whereas, the range 90 deg $< \theta_{r,\text{eml}} \leq$ 142.2 deg, Fig. 4(b), corresponds to an SGW reflection hologram.

Production of An SGW Hologram

Figure 5 shows a schematic diagram of a typical experimental setup for recording an SGW hologram. A laser beam is split into two parts by the beam splitter. One of the beams is expanded, passed through a spatial filter, and collimated by a convex lens to illuminate the object. The scattered light from the object reaches the hologram recording plate at nearly normal incidence. The other beam from the beam splitter is filtered and collimated before being introduced into the waveguide; typically a transparent block in the shape of a rectangular parallelepiped made from a material (usually glass or Plexiglas) with a refractive index close to that of the recording material.

SGW holograms require slightly more laser power than do their conventional counterparts. The relatively oblique incidence angle of the substrate guided reference wave causes less energy to be coupled into the recording material and absorption occurs as the reference wave passes through comparatively more optical elements. For these reasons, the efficiency of the system is usually increased by shaping the reference wavefront before it enters the substrate waveguide. This is accomplished in the setup shown in Fig. 5 by inserting a cylindrical lens and a 45-deg glass prism between the collimating lens and the transparent block. The cylindrical lens preserves collimation in the horizontal direction but causes the beam to diverge vertically. The prism is used to adjust the angle of incidence. The steep incidence angle of the guided wave, coupled with the diverging illumination, produces a relatively uniform illumination over the recording plane.

Figure 6 is a schematic of a fixture built to hold the block and hologram plate in place. The block/plate holder consists of a steel base, two supporting posts, and four positioning blocks. The main advantages of the holder are that it is mechanically stable and portable; the entire unit can be placed in a tray to avoid problems caused by leakage of the index matching fluid required to couple the recording plate to the substrate. Moreover, the design allows the block to be easily positioned and provides optical access for both the object and reference beams.

A glass plate is positioned between the bottom of the transparent block and the lower positioning blocks to create a platform to support the photographic plate. The height of the photographic plate is adjusted using an aluminum spacer; the horizontal position of the photographic plate is adjusted simply by sliding the spacer and the plate on the platform. Index matching fluid is used to laminate the photographic plate onto the block; additional pressure is placed on the edges of the photographic plate with a pressure plate connected to an externally mounted control rod. The inside surfaces of the pressure plate are painted black to avoid reflections which can interfere with hologram formation; the control rod and the pressure plate are locked into place by tightening a set screw.

After an SGW hologram is recorded, the photographic plate is removed and developed. The hologram is then repositioned on the block and viewed in a conventional manner. An alternative approach, as described later, is to mount the hologram on an optical substrate for display purposes.

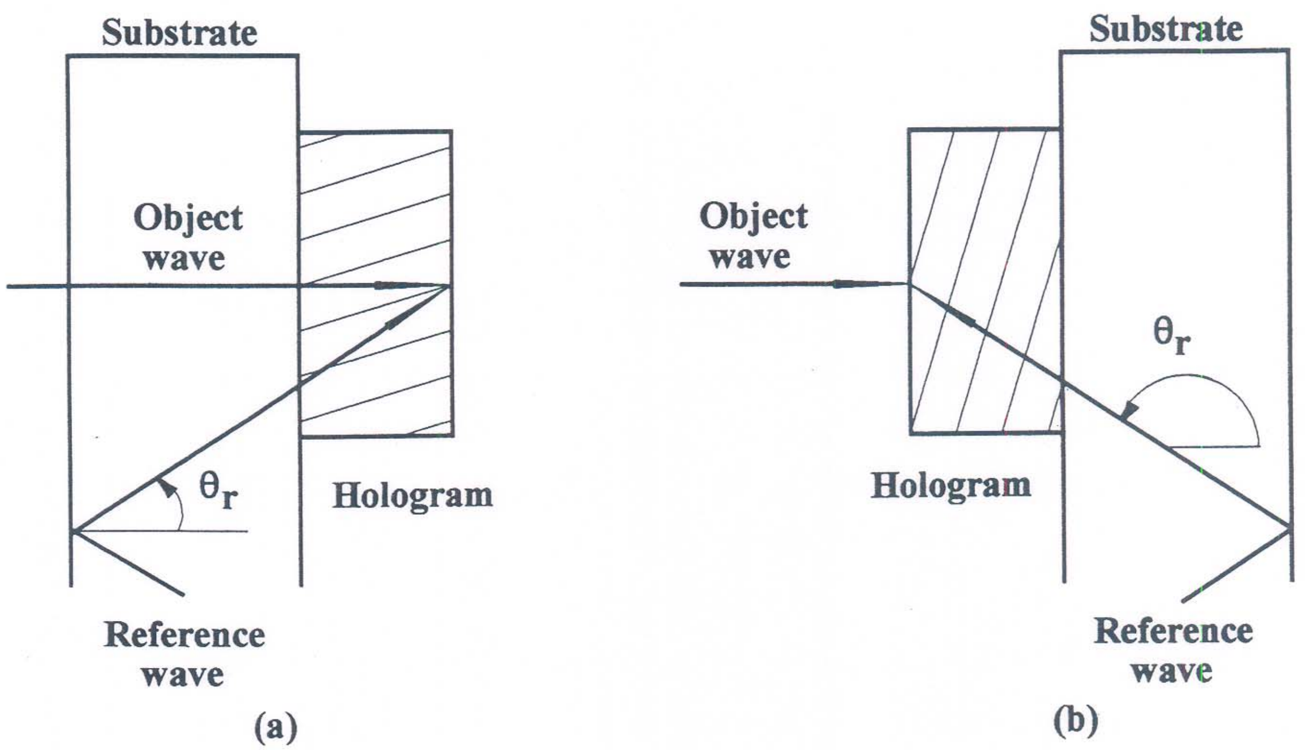

Fig. 4.—SGW hologram recording geometries: (a) transmission and (b) reflection

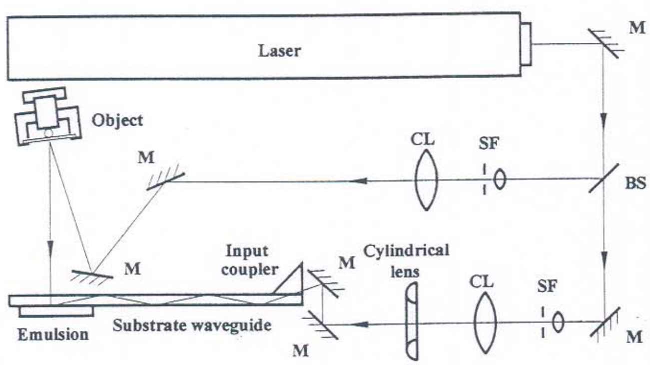

Fig. 5.—Experimental setup for SGW holography: M, BS, SF, and CL stand for mirror, beamsplitter, spatial filter, and collimating lens, respectively

Production of an SGW Holo-Interferogram

The experimental setup shown in Fig. 5 was used to study a 7.62-cm diameter edge-clamped, centrally loaded disk. The disk was positioned with the normal to its surface oriented along the angle bisector of the illumination and observation directions. In this case, the sensitivity vector is normal to the surface and the out-of-plane displacement, w, is given by[11]

$$w = \frac{n\lambda}{2 \cos \alpha} \tag{4}$$

where 2α (20 deg) is the angle between the propagation vectors in the directions of illumination and observation.

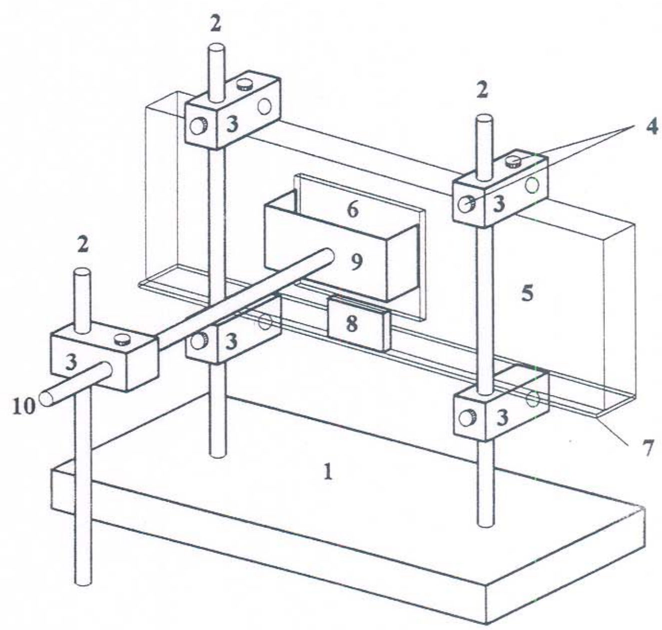

Fig. 6.—Block/plate holder: 1. steel base, 2. supporting posts, 3. positioning blocks, 4. set screws, 5. transparent block, 6. recording plate, 7. glass platform, 8. aluminum spacer, 9. pressure plate, and 10. control rod

A krypton laser, having an output power of 100 mW and a wavelength of 647 nm, was employed as the light source. The transparent block measured 20.32 cm × 12.70 cm × 1.27 cm and was made of acrylic (Plexiglas) with a refractive index of 1.49. The hologram was recorded on a 1.52-

mm thick, 6.35-cm square glass plate. The plate was coated with a 7-μm thick red-sensitive silver halide emulsion which had a sensitivity of approximately 75 erg/cm^2 at 633 nm and a resolution of approximately 3000 lines per millimeter.

The reference beam was guided into the waveguide at 70 deg with respect to the normal drawn to the front face. The prism and the silver halide plate were optically coupled, and mechanically attached, to the substrate using microscope immersion oil. This product has a refractive index of 1.52 which is as close as possible to the indices of the transparent block (1.49), the prism (1.50) and the recording material (1.63); the index matching fluid is also chemically inert when used with Plexiglas, glass and silver halide. Excess fluid can be easily removed using methanol.

Prior to mounting the photographic plate in the holding frame, the surface of the transparent block was cleaned with methanol. This step was important, since dust particles on the surface could have generated air pockets, thickened the fluid layer, caused nonuniformity in the fluid layer, scratched the surface of the block or made the recording plate difficult to remove. After the surface of the block was cleaned, the photographic plate was removed from its protective package and the emulsion side identified. Immersion oil was applied on the glass substrate side (the side opposite the emulsion). The photographic plate was laminated to the block by squeezing air out while sliding the plate back and forth over the surface. After the plate was laminated, it was allowed to rest on the aluminum spacer shown in Fig. 6. The pressure plate was positioned behind the photographic plate using the control rod. The entire system was allowed to stabilize for five minutes before exposing the hologram.

A holographic recording of the undeformed disk was made on the silver halide plate using a reference to object beam ratio of 4:1. The center of the disk was displaced under load 5×10^{-4} cm and a second holographic recording was superimposed on the initial recording. The double-exposure holointerferogram was processed using a developer/bleach kit. First, the exposed plate was removed from the transparent block and rinsed in methanol to remove the index matching fluid. The plate was then placed in the developer and agitated until the plate turned totally dark; it is preferable to overdevelop the plate, since nearly all of the silver is removed during the bleaching process. Then, the developed plate was rinsed in running water for about two minutes. The plate was placed in the bleach and agitated until the plate became transparent. Finally, the plate was rinsed in running water for five minutes, placed in a photoflo bath, and hung up to dry. Figure 7 shows a photograph of the image reconstructed when the processed double-exposure hologram was reattached to the substrate using matching oil and illuminated with the reference beam.

As mentioned previously, the fringe pattern corresponds to displacement measured normal to the plane of the clamped disk. The deflection of the disk at a distance r from its center is predicted to be[12]

$$w = \frac{Pr^2}{8\pi D} \log \frac{r}{a} + \frac{P}{16\pi D} (a^2 - r^2) \qquad (5)$$

where

$$D = \frac{Eh^3}{12(1 - \nu^2)} \qquad (6)$$

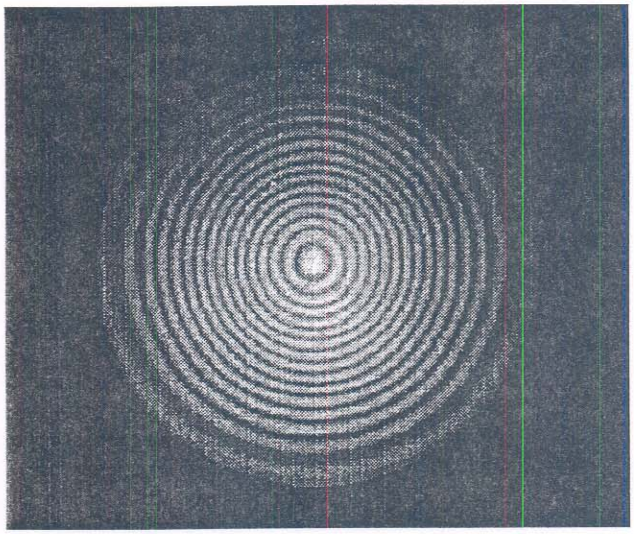

Fig. 7.—SGW double-exposure holointerferogram corresponding to the out-of-plane displacement of an edge-clamped, centrally loaded disk

Equations (5) and (6) are for a disk of radius a and thickness h with Young's modulus and Poisson's ratio of E and ν, respectively. The load, P, can be determined by knowing the center deflection imposed between exposures and a theoretical fringe map can be plotted over the full field. In this experiment: a = 3.81 cm, $E = 27.58 \times 10^5$ kPa, h = 0.318 cm, and ν = 0.35. For λ = 647.1 nm, the location and number of the fringes shown in Fig. 7 agree to within two percent of theory.

Archival and Display of SGW Images

The SGW hologram can also be permanently mounted on a relatively thin optical substrate having the same index of refraction as the transparent block used to record the hologram. The thickness of the substrate depends upon the application at hand; normally, the substrate thickness is on the order of 3-12 mm. The edge where the light enters the substrate needs to be optically polished. A viable alternative is to laminate a flat glass plate onto the edge using an adhesive having an index of refraction close to that of the glass and the substrate.

Hologram quality can be initially evaluated by temporarily laminating the hologram on the substrate using im-

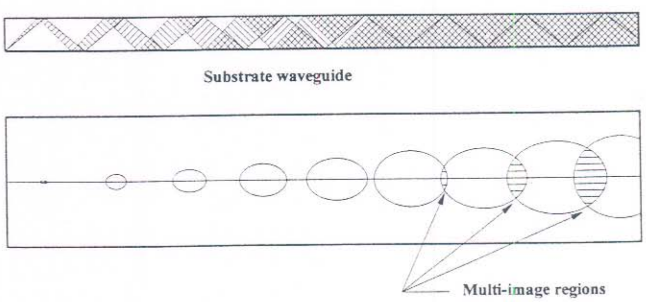

Fig. 8.—Multimode blurring may occur when light is launched into a relatively thin substrate

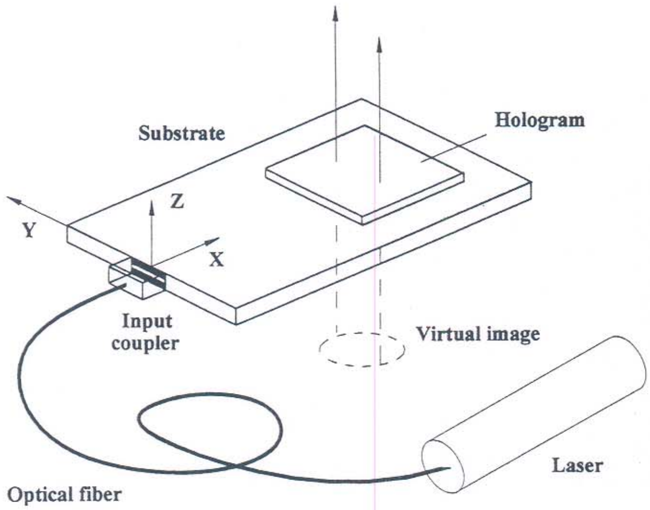

Fig. 9.—SGW hologram laser illumination system with an input coupler used to eliminate multimode blurring

mersion oil. Once a satisfactory result is obtained, the surfaces are cleaned and the hologram is glued to the substrate using UV-cured optical epoxy. In mounting the hologram, the glass side must be placed in contact with the substrate and the hologram must be oriented in precisely the same way that it was during the recording phase.

When the hologram is laminated in a location which is relatively far from the edge through which the illumination wave is coupled, more than one image may be reconstructed simultaneously. These multiple images overlap and degrade image quality. This effect, called multimode blurring, is caused by the angular divergence of the guided wave. Figure 8, for example, shows a diverging illumination beam with a circular cross section coupled into the substrate waveguide. The beam produces elliptical spots which grow in size as the beam reflects within the substrate. These spots will eventually overlap as illustrated by the shaded areas on the figure. If a hologram is placed over the shaded areas, multiple images are reconstructed. Since the illumination waves have slightly different incident angles, blurring occurs. As discussed below, an input coupler can be used to eliminate this problem.

Figure 9 shows one approach for reconstructing an SGW hologram using light from a He-Ne laser guided through a single mode fiber. A typical substrate would be a 5-mm thick Plexiglas sheet. The edges of the substrate must be polished to minimize distortions in the input beam and to allow the transmitted light to exit the substrate without back scattering. The hologram is laminated on the substrate with UV cured optical epoxy; multimode blurring is eliminated

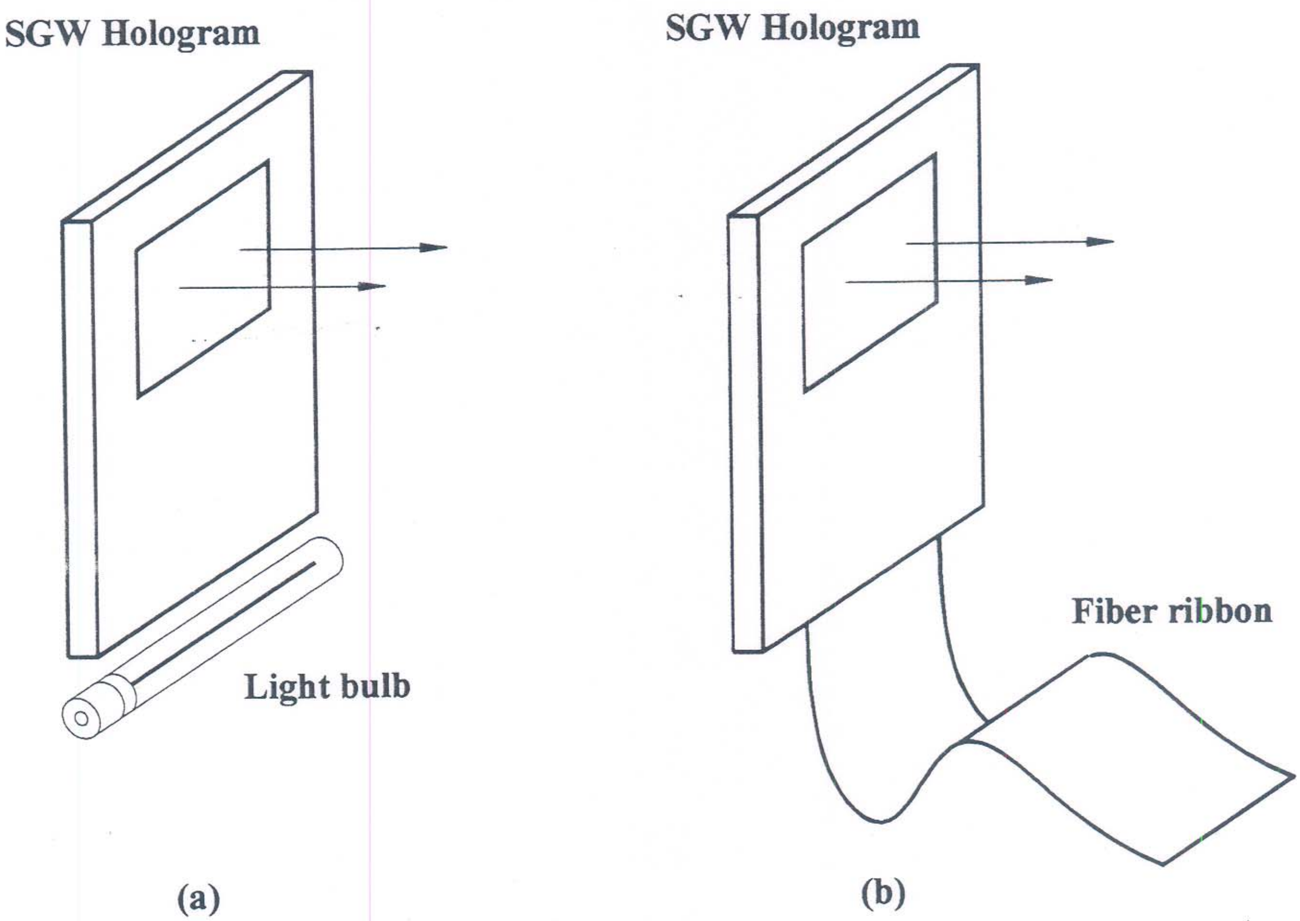

Fig. 10.—Methods for white light illumination of SGW image plane holograms: (a) tungsten light bulb and (b) fiber ribbon

by employing an input coupler between the exit end of the optical fiber and the substrate waveguide. The coupler consists of a small glass cube. Light is coupled from the fiber into one side of the cube using index matching fluid. A 0.5-mm wide slit is masked off on the opposite side of the cube to control the divergence of light within the waveguide.

The depth and the resolution of images reconstructed by the system illustrated in Fig. 9 are comparable to those obtained by reconstructing conventional transmission holograms. The only problem is that scattering within the holographic emulsion makes the image look somewhat foggy. This is accentuated by the relatively large grain size of silver halide; an alternate material such as dichromated gelatin substantially improves the result.

In contrast to reconstructing a deep three-dimensional image, an SGW hologram can be recorded using the image plane method. This is easily accomplished by inserting an imaging lens between the object and the recording plate. Because the two-dimensional image obtained is on or near the hologram plane, high spatial coherence is not required and the image may be reconstructed using an extended white light source or a fiber-optic ribbon. Figure 10(a), for example, shows how an image-plane SGW hologram may be illuminated with white light. The light source is a straight filament tungsten light bulb aligned with the edge of waveguide. In this case, the illuminated edge is polished while the other edges are covered with black tape to prevent light leakage. Figure 10(b) shows an alternative approach which utilizes a fiber-optic ribbon. Because the object beam produced by the image plane method has a very small bandwidth, the diffraction efficiency can be very high.

The above discussions demonstrate some of the potential attributes of SGW systems. They can be compact, portable and robust; in most cases, the optics are relatively easy to align.

Conclusion

Substrate guided wave (SGW) holography is a relatively new technique which relies on recording and illuminating a hologram with light waves transmitted through a substrate waveguide. The unique recording geometries associated with the technique make it possible to generate holograms with reference waves inclined at steep angles with respect to the recording medium thereby extending the range over which reflection and transmission holograms may be generated. The main advantage of the technique for nondestructive testing is that the reference wave is encapsulated.

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