SUBSTRATE GUIDED WAVE (SGW) HOLO-INTERFEROMETRY

by

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ABSTRACT

This paper describes a new tool for experimental mechanics called substrate guided wave (SGW) holo-interferometry. The approach relies on recording and reconstructing time-average, double-exposure, and real-time holograms using light waves guided to the hologram by a dielectric sheet, or substrate waveguide. The study illustrates that SGW holo-interferometry can be used to isolate the reference wavefront from the environment surrounding the hologram, and can be applied to measure the mechanical properties of the substrate itself. These attributes are discussed along with experimental work performed to develop and refine the technique.

1. INTRODUCTION

Holographic interferometry is a powerful and versatile tool in experimental mechanics and has been used productively for nondestructive evaluation to visualize flow fields, characterize vibration modes, reveal deformations, determine stresses and strains, and to detect cracks and subsurface flaws. However, there are some situations where investigators working with conventional approaches to holo-interferometry encounter difficulties and are unable to obtain satisfactory results. For example, it is virtually impossible to successfully record a meaningful interferogram under conditions where turbulent air, water, or other unstable environmental conditions produce changes in the index of refraction of the reference wavefront. Moreover, many holographic recording systems are complex and/or difficult to miniaturize. These and other problems can be partially solved by employing a new technique called substrate guided wave (SGW) holo-interferometry.

This paper includes a brief introduction to guided wave techniques and reviews some of the work underlying the development of SGW holo-interferometry. This new technique is described along with the equations required to interpret the associated fringe patterns. Experimental tests, conducted to demonstrate SGW holo-interferometry, also illustrate some of its potential advantages. Results show that the technique can be applied to record double-exposure, real-time, and time-average holo-interferograms.

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2. SUBSTRATE GUIDED WAVE HOLOGRAPHY

Substrate guided wave (SGW) holography relies on recording and reconstructing holographic images with light waves guided to the hologram by a dielectric sheet, or substrate waveguide. This technique originated from the basic concept of the edge illuminated hologram initially reported by Lin[1] in 1970. Suhara, Nishihara and Keyama[2] subsequently referred to the product of this holographic construction as a "waveguide hologram." Intensive investigations followed in which waveguide holograms were used in applications ranging from optical computing and information processing[3] to artistic displays.[4,5] Several interesting properties of waveguide holograms, recently discussed by Huang and Caulfield,[6,7] include the image-to-background contrast, multiple utilization of the illumination beam, the twin image effect, and the multimode image blurring effect.

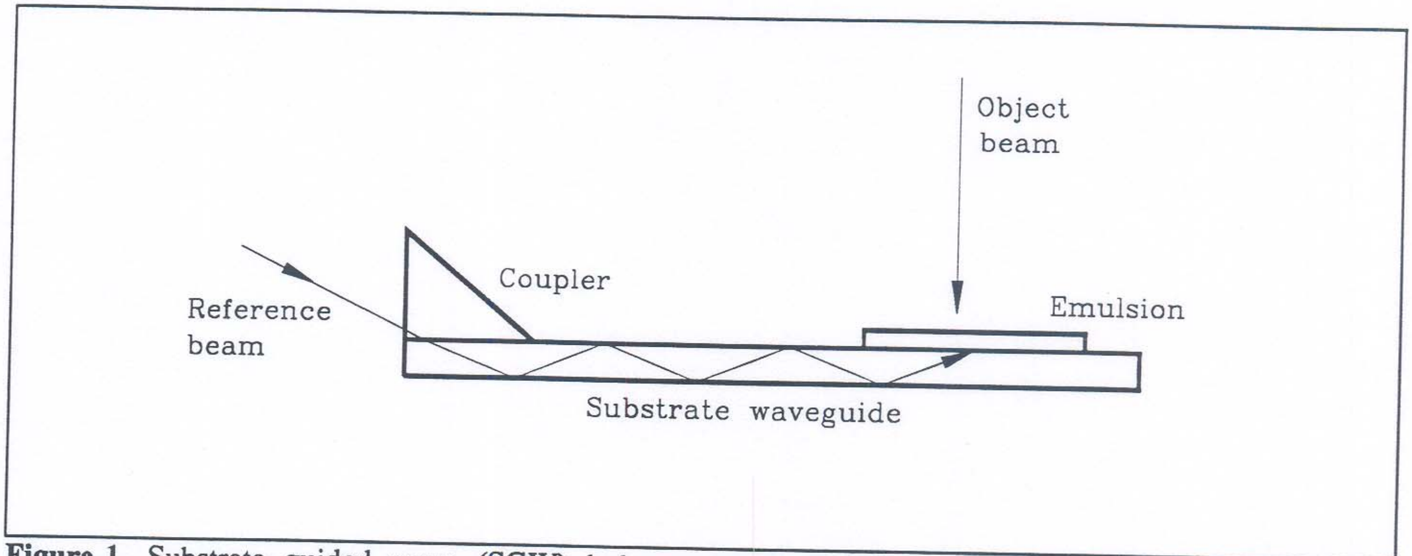


Figure 1. Substrate guided wave (SGW) holograms are recorded when the reference and/or object wavefronts are transmitted to the recording plane using a substrate waveguide.

As illustrated in Figure 1, light may be coupled by a prism, a grating, or other edge-lighting mechanism into a sheet of transparent material having two surfaces which are locally parallel and optically polished. When the index of the material is higher than that of its surroundings, light is transmitted through the substrate by total internal reflection. The waveguide is referred to as multimode, since different rays follow different coarse zigzag paths. A portion of the transmitted light can be coupled into a photosensitive emulsion (silver halide, photopolymer, dichromate gelatin, or photoresist) placed in direct contact with the substrate. When the portion of the light guided by the substrate is used as a reference and/or object wavefront for holographic construction, the process is referred to as substrate guided wave (SGW) holography.

There are several distinct advantages of using the SGW approach over more conventional holographic recording methods. The optical systems used to reconstruct conventional holograms are often complex and may require considerable alignment; the light source must have good spatial coherence (for reflection and rainbow holograms) and temporal coherence (for transmission holograms); off-axis illumination increases the size of the overall recording system while undiffracted light, passed through the hologram, poses a safety hazard to the viewer. SGW holographic systems, on the other hand, are portable, robust, and relatively easy to align. A monomode fiber, for example, may be used to guide light to a hologram placed in direct optical contact with the substrate. In addition, the illumination may be edge introduced and guided by total internal reflection through the substrate. Consequently, the system is compact and can be easily miniaturized. Moreover, the illuminating beam is encapsulated within the substrate and only the holographic image is diffracted. This allows the hologram to be viewed close to the recording plane without the danger of eye damage associated with the undiffracted light produced during off-axis reconstruction.

3. HOLOGRAPHIC INTERFEROMETRY

Unlike ordinary photography where only the amplitude of the light intensity is recorded, the holographic process records both the phase and amplitude of the light scattered from an object. Phase information is important, since comparisons can be made between holograms recorded as a test surface moves. This process, called holo-interferometry,[8-10] produces a set of interference fringes which may permit the detection and measurement of surface displacement.

The time-average technique, developed by Stetson and Powell[11] may be used to reveal contours of constant amplitude on the surface of a vibrating object. In this technique, a holo-interferogram is produced by generating a hologram by exposing a film plate for a period of time during which the test object executes many cycles of steady vibration. In this case, the intensity of the reconstructed image is

$$I \propto J_o^2 \left[\frac{2\pi}{\lambda}(\mathbf{g} \cdot \mathbf{d})\right] \qquad (1)$$

where λ is the wavelength of the coherent light used to record and reconstruct the hologram and **d** is the displacement vector of the surface point under consideration. The sensitivity vector **g** is defined by ($\hat{\mathbf{e}}_2$ - $\hat{\mathbf{e}}_1$); $\hat{\mathbf{e}}_1$ and $\hat{\mathbf{e}}_2$ are unit vectors in the directions of illumination and observation, respectively.

The variation in intensity is characterized by being a maximum when the argument of the Bessel function is equal to zero, and having succeeding maxima which decrease in value. When the displacement is zero, the reconstructed image is the brightest; consequently, regions having no motion, or nodes in the vibratory pattern, exhibit the greatest intensity. Dark fringes occur at the roots (zeros) of J_o^2; the particular root on the interferogram may be determined by counting from the nearest stationary point on the object, marked by the very bright fringe corresponding to the nodal location. The roots of J_o are tabulated and their values may be used together with the known values of the sensitivity vector to determine the amplitude of the object motion in the direction of the sensitivity vector.

If a hologram is recorded of the object while it is vibrating in only one of its vibration modes, then a photograph of the reconstruction from that hologram will display the vibration mode in a simple topographical map of fringe contours. For example, with normal illumination and observation,

$$N_i = \frac{4\pi w}{\lambda} \qquad (2)$$

where w is the displacement component along the line of sight and N_i are the roots of the Bessel function. This presumes that the sensitivity vector is essentially constant across the surface of the object, and that the vibratory motion is unidirectional. If this is not the case, vibration analysis may require more than one holographic perspective per mode.

A second technique, usually referred to as double-exposure holo-interferometry, generates a high contrast fringe field by interfering two object wavefronts reconstructed from the same doubly exposed hologram. In this case, dark cosine fringes appear in the space around the test object. These fringes are associated with the changes in optical pathlength resulting from changes in the test object occurring between exposures. As such, double-exposure holo-interferometry provides a permanent record of the phase changes which occurred between exposures, but no history of information describing the changes over time as they actually occurred.

Real-time holo-interferometry, on the other hand, provides a cosine fringe field which changes as the test object changes. Fringes are generated directly by interfering the actual coherent wavefront from the object with a reconstructed holographic "reference" wavefront. In order to generate high contrast real-time fringes, this approach requires that the object illumination and reconstructing reference beams be adjusted to yield object wavefronts of nearly equal intensity and that both beams and the hologram be located in exactly their original positions relative to the test object during reconstruction of the reference wavefront. This latter (most critical) requirement can be met, though with some difficulty, by precise repositioning of the hologram after its removal for processing elsewhere; or, more effectively, by processing the hologram in place.

Fringe patterns, obtained using either the double-exposure or the real-time approach, are governed by

$$n\lambda = \mathbf{g} \cdot \mathbf{d} \qquad (3)$$

where n is the fringe order number, λ is the wavelength of the coherent light used to record and reconstruct the hologram, and **d** is the displacement vector of the surface point under consideration. As discussed earlier, **g** is the sensitivity vector defined by $(\hat{\mathbf{e}}_2 - \hat{\mathbf{e}}_1)$.

In these cases, the observed displacement fringes are due to the change in optical path which occurs between recordings. These pathlength changes give rise to a distribution of phase differences between the reconstructed wavefronts which results in areas of constructive or destructive interference and are seen as a set of light and dark fringes. The component of displacement measured at each point depends upon the location of the source and on the point of observation; the displacement vector is projected along a sensitivity vector which coincides with the angle bisector of $\hat{\mathbf{e}}_1$ and $\hat{\mathbf{e}}_2$. Therefore, when a relatively flat surface is oriented normal to the angle bisector of $\hat{\mathbf{e}}_1$ and $\hat{\mathbf{e}}_2$, the interferometer senses only the out-of-plane displacement component, w, and Equation (3) becomes,

$$n\lambda = 2w\,(\cos\varphi) \qquad (4)$$

where 2ϕ is the angle between the propagation vectors in the directions of illumination and observation.

4. SGW HOLO-INTERFEROMETRY

When recording holo-interferograms, the reference wavefront needs to be stable during and between holographic recordings. Unfortunately, perturbations caused by changes in the environment surrounding the hologram are difficult to avoid in conventional holographic systems. On the contrary, SGW systems can be designed to protect the guided wave from these perturbations. Moreover, the guided wave may be used as the object beam so that changes in the mechanical, thermal or optical response, and physical properties of the substrate, can be measured.

The following section describes a series of tests conducted to illustrate these attributes and demonstrates that double-exposure, real-time, and time-average interferograms can be recorded and reconstructed using the SGW approach.

5. EXPERIMENTAL

Figure 2 shows the basic set-up used to record SGW holo-interferograms. A 20 cm x 12 cm x 2 cm PMMA block is used as a substrate to guide light from a 100 mw krypton laser to a 6 cm x 6 cm, Agfa 8E75 silver halide plate. The oblique incident angle of the reference beam, equal to approximately 70°, is controlled using a combination of mirrors. A cylindrical lens is used to diverge the incident beam in the vertical direction before it enters the substrate. A 45° glass prism is used to guide light into the substrate; the prism and the silver halide plate are optically coupled, and mechanically attached, to the substrate using index matching oil. The steep incidence angle of the guided wave, coupled with the diverging illumination, produce a relatively uniform illumination over the recording plane.

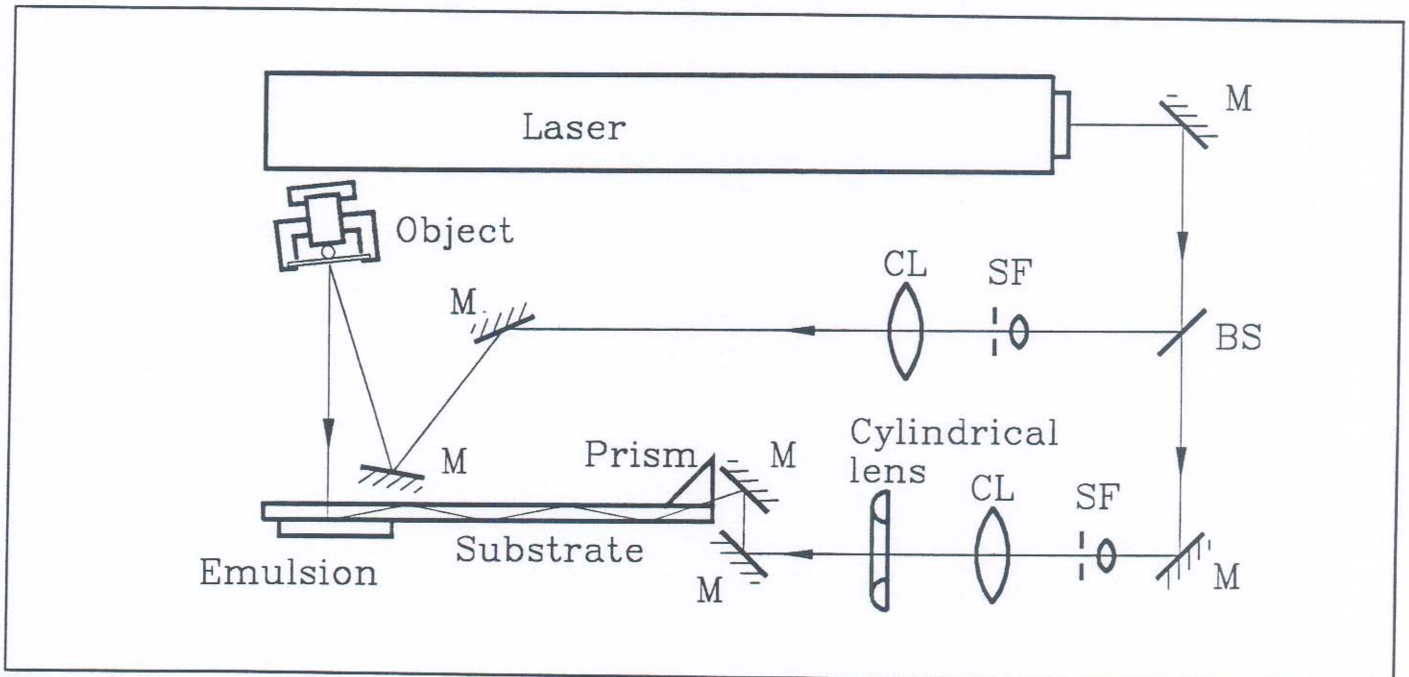


Figure 2. Experimental set-up used to record substrate guided wave holo-interferograms; M, BS, SF, and CL stand for mirror, beam splitter, spatial filter, and collimating lens, respectively.

The set-up shown in Figure 2 was used to study a 7.62-cm diameter edge-clamped, centrally loaded disk. The disk was positioned with $\phi = 10°$; that is, the normal to its surface was oriented along the angle bisector of the illumination and observation directions. In this case, the sensitivity vector is normal to the test surface and Equation (4) holds. A holographic recording of the undeformed disk was made on the silver halide plate. 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 silver halide plate was removed from the substrate and developed in a darkroom. Figure 3 shows the reconstruction when the processed double-exposure hologram was reattached to the substrate using matching oil and illuminated with the reference beam. The fringe pattern corresponds to displacement measured normal to the plane of the clamped disk. In this case, the deflection of the disk at a distance r from its center is given by[12]

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

where

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

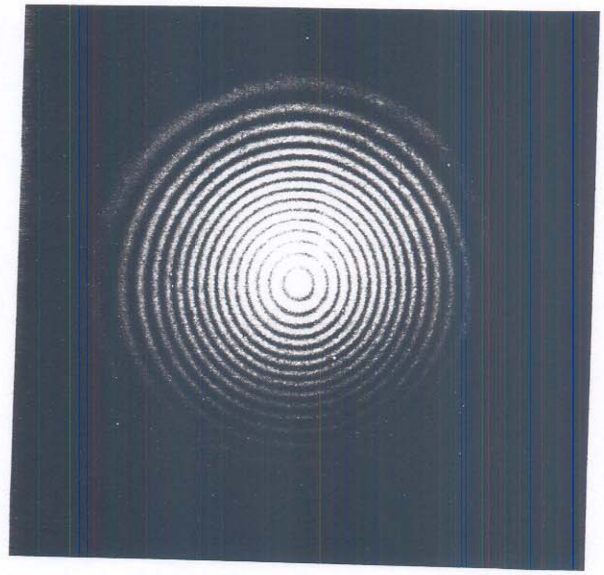


Figure 3. Holo-interferometric fringe pattern corresponding to the out-of-plane displacement of an edge-clamped, centrally loaded disk.

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 x 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 Figure 3 agree well with theory.

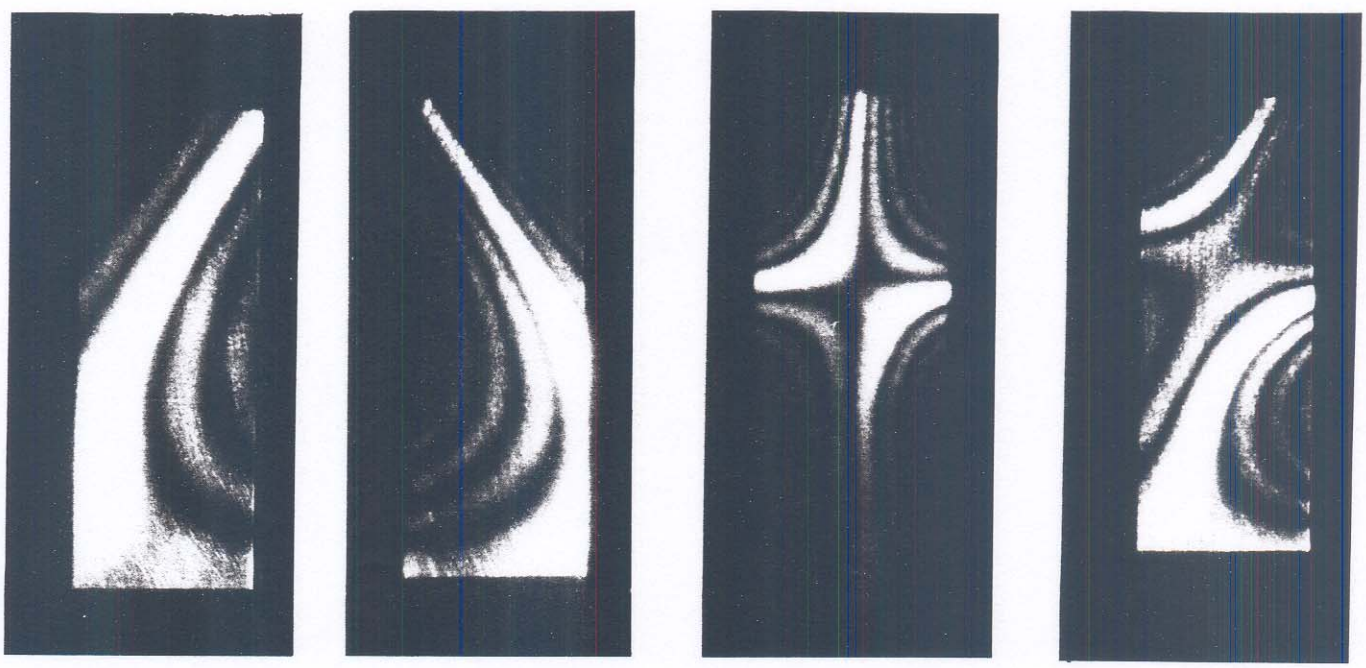
One of the major factors inhibiting full exploitation of holo-interferometry is the difficulty of getting quantitative results from the holographic interferograms. Indeed, by itself the interferogram does not even contain sufficient information to determine the direction or sign of the surface displacement component being measured. This is illustrated in Figure 3 which corresponds to an outward movement of the disk; the same pattern would have resulted had the disk moved inward. This problem can be solved by utilizing the method of carrier fringes.[13] The objective of this method is to superimpose a monotonic phase change across the field of view; ideally, the carrier pattern should be localized on the surface on the specimen. The approach is to superimpose a known carrier with the deformation and then to subtract the carrier. This process is conducted by digitizing the two interferograms and computationally subtracting the fringes.[14] Carrier patterns can be generated by moving the specimen, changing the illumination or reference beams, or moving the hologram itself.

Well-localized carrier fringes can be generated quite easily in SGW holo-interferometry. Figure 4(a), for example, shows the reconstruction of a carrier pattern produced by slightly changing the incident angle of the light coupled into the waveguide. In this case, the interference fringes localize in the plane of the silver halide emulsion; however, a simple lens can be used to image the object surface onto the plate. This approach not only maintains proper localization but reduces the coherence requirement on the source used for reconstruction, thereby, allowing holo-interferograms to be viewed using white light. Figure 4(b) shows the modulated carrier recorded after the disk is loaded. Figure 4(c), on the other hand, shows the circular fringes, produced in the form of a moire pattern, when the holo-interferograms shown in Figures 4(a) and

4(b) are optically superimposed. Figures 4(a), 4(b) and 4(c) were all reconstructed using white light.

(a) (b) (c)

Figure 4. The method of carrier fringes can be used to determine the sign of the displacement component being measured; (a) carrier pattern, (b) modulated carrier pattern, (c) optical superposition of (a) and (b).



(a) (b) (c) (d)

Figure 5. Time average holo-interferograms showing torsional modes recorded on the surface of a cantilever beam acoustically excited into steady-state vibration using a loudspeaker; (a) 949 Hz, (b) 1165 Hz, (c) 2981 Hz, (d) 3088 Hz.

A third experiment was performed by imaging the front surface of a 7.62 cm long, 2.54 cm wide, 0.07 mm thick cantilever beam onto the recording plane using a simple lens. The cantilever beam was acoustically excited into steady-state vibration using a loudspeaker positioned behind it. An accelerometer, mounted on the rear upper corner of the free end of the cantilever, was used to detect resonant frequencies. Figure 5 shows reconstructions of four time-average holograms, each recorded with an exposure time of three seconds. The fringes in the patterns represent movements normal to the surface of the cantilever. Figures 5(a) and 5(b) correspond to first torsional modes recorded at frequencies of 949 Hz and 1165 Hz, respectively; while, Figures 5(c) and 5(d) correspond to second torsional modes recorded at 2981 Hz and 3088 Hz, respectively. The patterns are slightly different from those predicted on the basis of theory; however, anomalies can be attributed to the eccentric mass loading produced by the accelerometer.

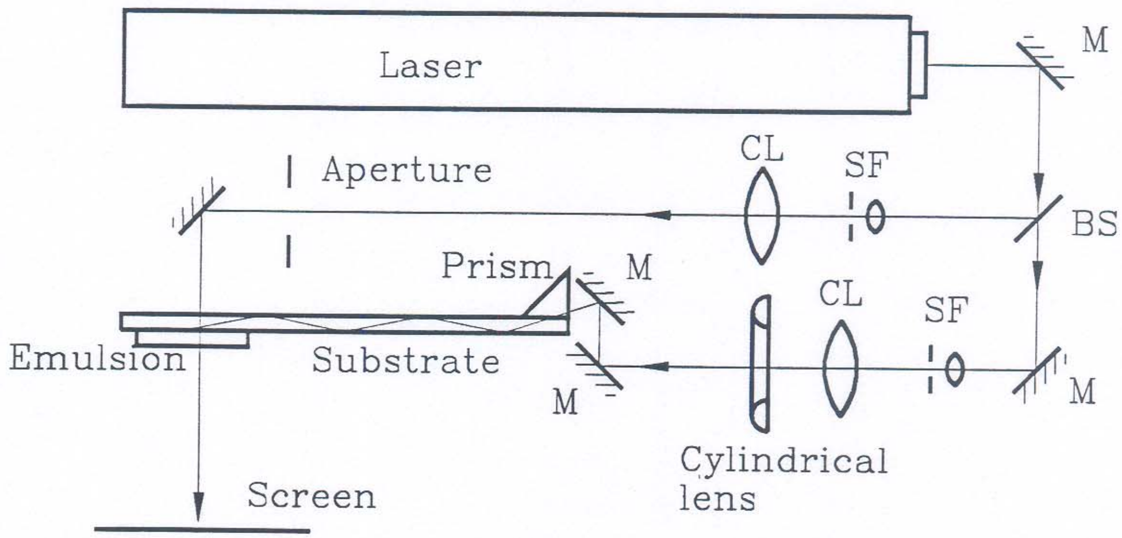
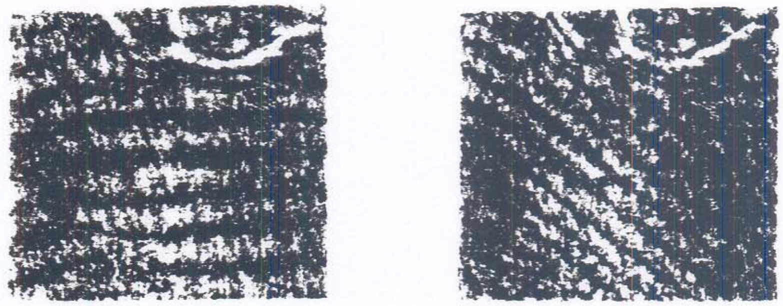


Figure 6. Experimental set-up used to demonstrate that the response of a substrate can be monitored using real-time SGW holo-interferometry; M, BS, SF, and CL stand for mirror, beam splitter, spatial filter, and collimating lens, respectively.

The carrier fringe method can be applied with real time holo-interferometry to observe changes in the substrate itself. The experimental setup shown in Figure 2 can be modified, as shown in Figure 6, by replacing the object with a mirror and adjusting the optical configuration to produce a collimated wavefront. A silver halide plate, positioned on the substrate, can be used to holographically record the complex diffraction grating corresponding to the interference between the free space and guided waves. After development, the hologram is repositioned on the substrate and reconstructed using the guided wave. The location of the hologram can be adjusted to minimize the fringes produced in real-time by the interference between the reconstructed and actual collimated wavefronts; thereby, creating an SGW holo-interferometer. Subsequent modulation of the substrate produces additional fringes which can be viewed on a screen located behind the hologram, in the path of the reconstructed beam.

A test was conducted to illustrate this approach by generating and repositioning a hologram as described above. The guided wave was subsequently adjusted to produce the set of horizontal carrier fringes shown in Figure 7(a). Figure 7(b) shows the modulated carrier pattern produced when a portion of the substrate was heated. The orientation and spacing of the fringes can be related to thermal response of the substrate. Future work will report further on the development of such SGW sensors.



(a) (b)

Figure 7. Holo-interferograms recorded before and after a substrate was heated; (a) initial carrier pattern, (b) modulated carrier pattern.

6. CONCLUSIONS

It has been demonstrated that SGW holo-interferometry is a powerful new tool for nondestructive testing. Double-exposure, real-time, and time-average fringe patterns have been generated. A well-localized carrier pattern can be introduced simply by modulating the incident angle of the reference beam guided through the waveguide. Moreover, the substrate can be monitored and used as a sensor.

7. ACKNOWLEDGEMENTS

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