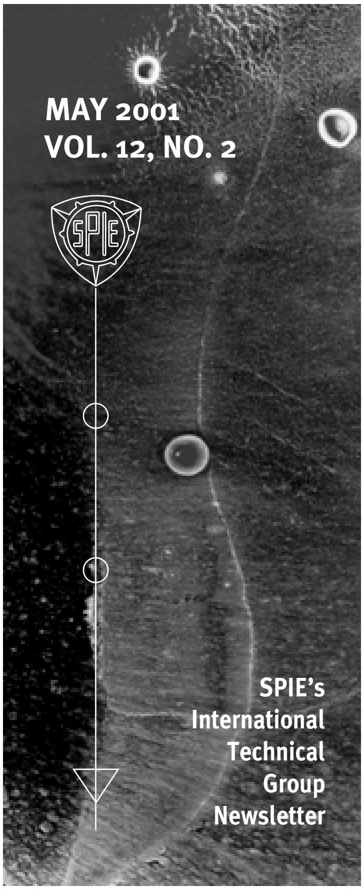

HOLOGRAPHY

Fiber Bragg Gratings: Holograms in time and frequency

Holography was originally conceived as a technique allowing for the reconstruction of a three-dimensional wavefront from an amplitude and phase profile encoded on a two-dimensional medium. Since its discovery by Dennis Gabor in 1948, spatial holography has developed into a powerful optical tool, with applications in displays, security, filtering, and optical signal processing.

In the past decade, a number of groups have generalized holography to the treatment of observables other than position and angle. In particular, it is possible to process both the spectral and temporal components of a time-varying optical signal by using the properties of optical diffraction. These techniques fall under the denomination of spectral holography, and are finding increasing applications in optical fiber communications.

Fiber Bragg Gratings (FBGs) are an application of spectral holography that is of growing commercial importance. A fiber Bragg grating consists of an optical fiber whose core contains a longitudinal phase modulation. As an optical signal propagates along the FBG, portions of its optical spectrum are reflected by sections of the grating that nominally satisfy the Bragg condition: $\lambda = 2n\Lambda$, where λ denotes a specific spectral component of the signal, n is the effective average refractive index of the fiber core, and Λ is the period of the grating section.

Essentially a FBG acts as an extremely selective one-dimensional volume hologram. While the interaction length in a display reflection hologram is on the order of 10μm (determined by the thickness of the recording medium), FBGs have typical lengths measured in centimeters. Because of the very long interaction length, it is possible to manufacture extremely selective filters that are widely used in dense wavelength division multiplexing (DWDM) communication systems. As an example, 0.2nm bandpass filters (corresponding to a 25GHz bandpass) are commercially available as 2cm long FBGs. Because the medium is essentially lossless over centimeters, pure phase gratings exhibiting a reflectivity better than 99.9 % at the Bragg wavelength are common.

Chirping a grating along the length of a fiber results in different wavelengths being reflected at successive times as the signal propagates down the fiber core. Such gratings can be used to undo the chromatic spread a light signal experiences when propagating over long distances. Those so-called dispersion compensators constitute another important commercial application of FBGs.

The dispersion compensator exemplifies one of the main attractive features of FBGs, which is the possibility of manipulating the spectral components of a signal in the time domain. Indeed, FBGs can be

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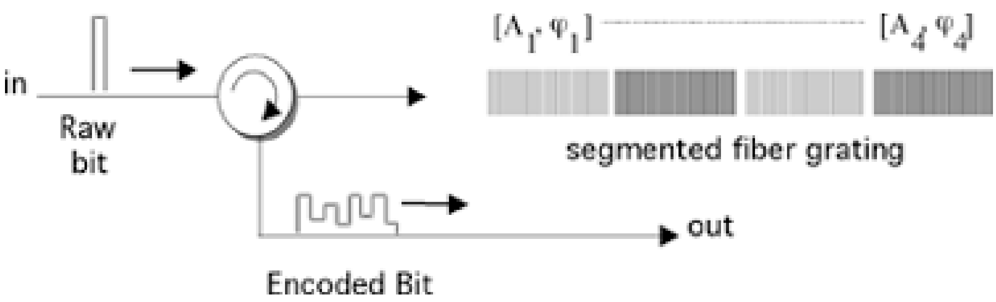

Figure 1. Spectral-temporal encoding with a fiber Bragg grating.

Special Issue:
Hidden Holography
Edited by **Sunny Bains,** Scientist/Journalist

Newsletter now available on-line

Technical Group members are being offered the option of receiving the Holography Newsletter in an electronic format. An e-mail notice is being sent to all group members advising you of the web site location for this issue and asking you to choose between the electronic or printed version for future issues. If you have not yet received this e-mail message, then SPIE does not have your correct e-mail address in our database. To receive future issues of this newsletter in the electronic format please send your e-mail address to spie-membership@spie.org with the word HOLOGRAPHY in the subject line of the message and the words "Electronic version" in the body of the message.

If you prefer to continue to receive the newsletter in the printed format, but want to send your correct e-mail address for our database, include the words "Print version preferred" in the body of your message.

Guest Editorial

When I started to write about holography back in 1986, my main interest was display. However, in those days, "holography" was a big field that also included holographic optical elements (HOEs), holographic interferometry, holographic memories, holographic optical interconnects, etc.. At conferences, all these different strands would be represented. Researchers dabbled in other areas, they all knew each other, they borrowed (and sometimes stole) ideas.

Now, we all seem to have gone our separate ways, we have our separate conferences, and the only people who still call themselves "holographers" seem to be in display.

As for me, I ended up being drawn away from holography by optical computing, thanks to some of the early papers on holographic optical correlators and neural networks, and then moved into emerging computing technologies generally. But, in parallel, I started writing a lot about optoelectronics, and found huge numbers of structures that looked like holograms there: what is a Fabry-Perot filter but a thin-film construction of a hologram? And I continue to follow holographic interconnects, memories, interferometry etc..

What still strikes me, is just how fundamental the idea of holography—the reconstruction of wavefronts—really is, and how much more prevalent it is in technology than most "holographers" realize. Though we may all be so specialized these days that it makes sense for us to go to our own conferences, I believe that it's important to keep looking over our technological neighbors' shoulders to see what they're doing. That way we may be able to both cross-fertilize and, more importantly, avoid having to reinvent the wheel.

The idea of this special issue was simply to give a flavour of some of the many ways that holography is still being used that we don't often cover here. I hope it will inform, and perhaps even inspire.

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Artists' Corner

New installation opens in Charlotte, NC

In collaboration with Ward Bos, an artist from Amsterdam, I recently completed a lobby installation for a new office complex in Charlotte, North Carolina. This work explores the properties of light and space using two art forms that transform light and space in distinctly different ways. The juxtaposition of painting and holography create multiple illusions that challenge the viewer's visual perception.

Odyssey 2001 is a site-specific installation that consists of three painted panels, in the form of a triptych being opened, and twelve holographic plates. Ten holograms are mounted in the panels, which are positioned flush to the wall, while the two holograms above and below the center panel are angled fifteen degrees away from the wall. The holographic images were produced on red sensitive BB plates made in Germany. The blue/green color of the holograms was created with water and alcohol, using a liquid gate.

Odyssey 2001: collaboration between Ward Bos (painting) and Rudie Berkhout (holography), at the Bank of America Technology Center, Charlotte, NC.

Shape and placement of the elements suggest an illusion that negates all spatial dimensions. The artwork seems to enter space, and makes the wall disappear. When we move, the space inside the hologram appears to change. Because of their relative relationships, even these fixed glass plates seem to move themselves, wanting to escape the opened triptych. They start their journey into space, each with their own direction and world within.

A different approach to working with light and space and a similar search for new dimensions, are the driving forces behind the collaboration. Odyssey 2001 is the first in a series of joint projects.

Rudie Berkhout
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LAB NOTES: Stretching light with aperture scanning

Most of us have a limited photon budget and are always trying to make it go a little farther: here is a method I use to stretch my coherent light. I call it *aperture scanning* because I usually arrange to scan the aperture of a spatial filter or, sometimes, a larger lens. The biggest loss of light for me is due to the very unfavorable power distribution in all Gaussian beams. I use dielectric mirrors wherever I can and avoid tiny pinholes as much as possible, but I need flat-top power distribution in at least my reference beam—and usually the same in my object beam—because I make large gratings and HOEs.

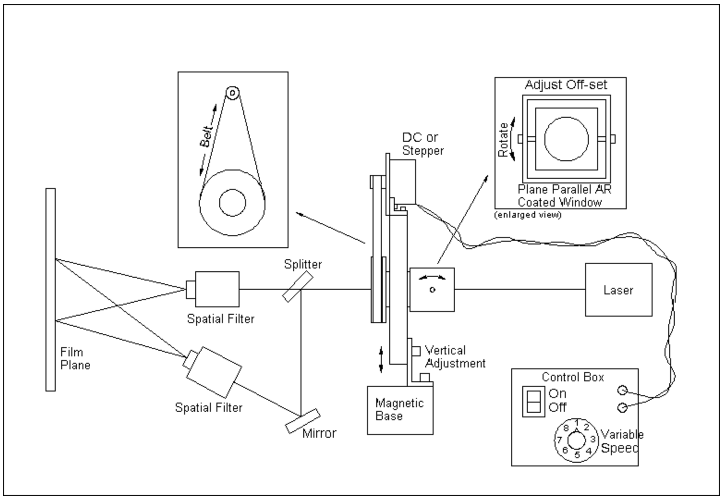

Figure 1. Circular aperture scanner.

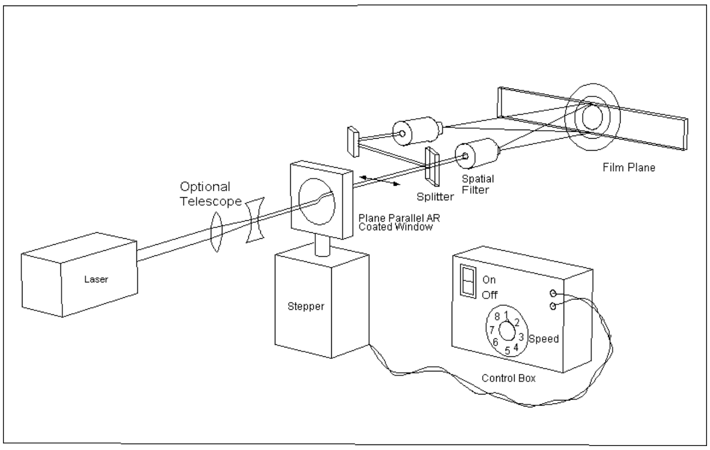

Figure 2. Linear aperture scanner.

There are many clever tricks to reshape the power distribution using combinations of lenses or diffractive optics, but none are very useful after a spatial filter. The diffractive or holographic optics always redistribute energy at the cost of speckle, dirt and loss of uniform phase. The lens tricks work while preserving phase, but cannot be easily adapted to all spatial setups because they require fixed distances to uniform planes and are hard to keep clean. The preferred method of getting clean recordings is to insert nothing between the pinhole and the recording plane with the exception of floppy masking, because the latter moves during exposure and therefore disappears. If you need uniform light, you generally have to overfill the recording plane and toss out as much as 90% of the light entering the spatial filter. This greatly limits the size of recording that can be made with a fixed amount of light.

Aperture scanning is completely general, it will work in all two-beam recording setups, with the single stipulation that each path contain equal reflections or equal plus *2n* reflections (where *n* is an integer) prior to the spatial filters and/or film plane. This rule just assures that scanning will be synchronous in direction at the film plane and much more likely to overlap. The scanner itself may not be allowed to change the angle of the incoming light, so it consists of a moving plane parallel window about 5-10mm thick. Sometimes it is helpful to reduce the diameter of the beam just prior to either the scanner or the spatial filters. This is easily done with a Galilean telescope or one positive and one negative lens suspended in air and adjusted for appropriate beam waist size. The narrowest beam waist should usually be at the aperture of the spatial filter, but this is an added degree of freedom in filling the film plane. This small waist allows us to work with a larger F# than the filter was made for, and therefore we can use a larger pinhole and still get good clean light with much easier alignment and less sensitivity to drift. I have used 40× and 60× objectives with 25µm pinholes just by reducing the beam waist to 100 or 200µm.

The scanner mechanics come in two flavors: one is for square or circular film planes, and the other for rectangular planes. The circular scanner holds the deflecting window at a tilt angle, adjusted to offset the hot spot at the film plane by about one third of its diameter. Then, it is rotated in the other plane so that it generates a filled donut of hot spots. Figure 1 shows a circular scanner with associated optics and electronics. A variable-speed motor of any type may be used, along with a belt, chain, or gear, and the window can be nested in a simple shaft or pillow-block bearing in a variety of ways (one of which is shown). The linear scanner in Figure 2 is even simpler. A parallel window, preferably anti-reflection coated on both sides, is mounted directly onto the shaft of a stepper-motor and is simply driven at the appropriate rate to move the hot spot from end to end during the required exposure time. Both methods may also be used at higher spin speeds so that the scanning is repeated many times during the exposure period and both scanners are simply inserted in-line after all other normal setup procedures are completed.

This technique works because the apparent source location of the illumination light never changes. This condition will not be met if anything but a parallel plate is used to deflect or displace the light. The tolerable error is a function of path lengths and angles and is probably less than a milliradian, so a fair test for a plate is to reflect a raw laser beam off both surfaces in a retro direction and far down stream check to make sure that the two spots are always at least partially overlapping. The linear scanner is not linear in scan rate, so a thicker window is appropriate to reduce this effect.

I hope this has been helpful to someone starved for optical energy.

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Spatiotemporal digital microholography

Gabor's invention[1] is an ingenious way of recording and reconstructing complex wave fields. The original motivation was three-dimensional (3D) microscopic imaging. Specifically, the goal was to overcome the serious limitations of the early electron microscopes.[2] The availability of the laser made this invention practical,[3,4] but serious drawbacks have limited its success as a 3D imaging method in the biological sciences.

The most troublesome drawback turned out to be the ubiquitous speckle noise associated with the high degree of coherence needed to record off-axis holograms.[5] The size of a speckle is the same as that of a resolution element, thus making it impossible to make use of the full resolution of the microscope objective. Invariably, speckle noise reduction results in a compromised resolution limit. The other drawback is the very high spatial resolution requirement imposed on the detector in order to accomplish the complex wavefront reconstruction by spatial heterodyning, as is done in conventional holography.[5] In the 50 years following Gabor's invention and Leith's demonstration of laser holography, an impressive number of ingenious ideas and methods have been proposed and demonstrated to try to alleviate these drawbacks.

In recent years, digital holography, in which the reconstruction is accomplished via computer, has emerged as a very useful quantitative microholographic method.[6,7] These advances were driven by the availability of fast, high-resolution solid-state detectors based on charge-coupled devices (CCD). The availability of fast computers and affordable memory also made it possible to take advantage of modern phase-extraction algorithms such as phase-shifting methods. Nevertheless, to a large degree, the old drawbacks of microholography have remained.

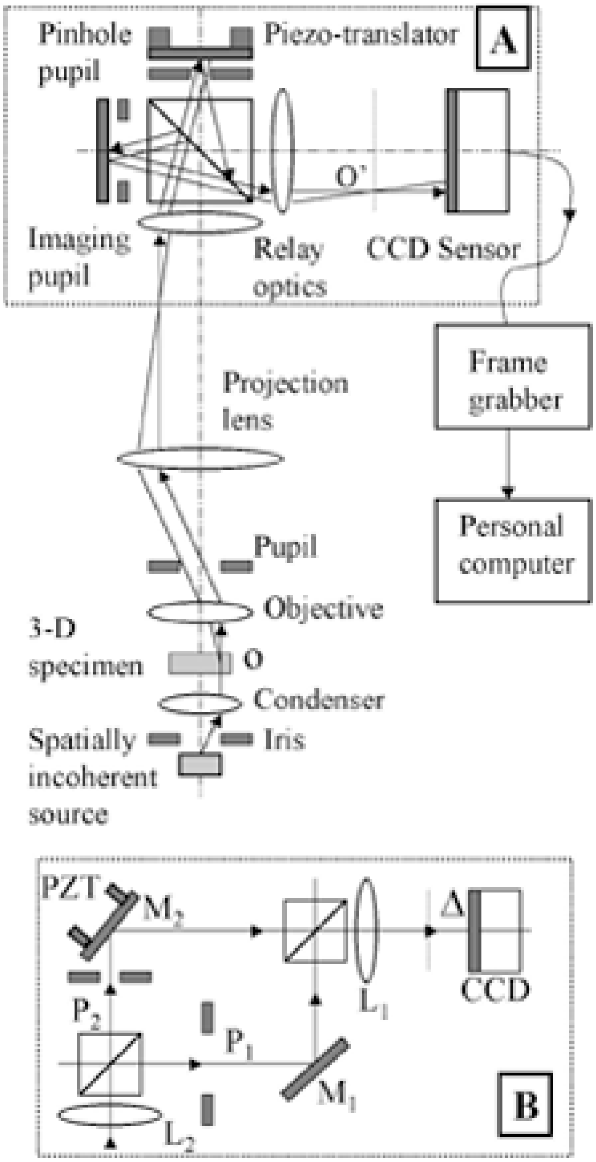

Figure 1. Sketch of a holographic microscope to record digital holograms in the time domain. The interferometric head, which can be implemented as either A or B, with frequency offset produces a temporally modulated on-line hologram recorded on a CCD sensor. The amplitude and phase at each pixel are stored as the holographic data.

Holography using space and time

Motivated by the desire to take full advantage of both the spatial and the temporal capabilities of modern CCD detectors, we have explored ways in which these could be used to alleviate the fore-mentioned problems of microholography.[8-10] CCD detectors not only offer high spatial resolution (1024×1024 elements is common), but they also can record the temporal evolution of the holographic fringes at high frame rates. With this additional dimension, it becomes possible to encode a complex wavefront in the time domain rather than in the space domain. The reconstruction of the complex wavefront is then accomplished using temporal heterodyning rather spatial heterodyning. The immediate advantages are substantial. Namely, both the coherence requirement and the spatial bandwidth requirement are considerably relaxed. It is now possible to record high resolution, on-line holograms of microscopic specimens with a degree of spatial incoherence that virtually eliminates the speckle noise without compromising the spatial resolution of the microscope.

One possible implementation of the idea is illustrated in Figure 1. This is a standard microscope with a fairly small light source providing just enough spatial coherence to produce on-line holographic fringes. The interferometer (A or B in Figure 1) provides a high-resolution image in one arm, and a local reference beam for each object resolution element in the other arm. One of the mirrors is translated to offset the temporal frequency by an amount compatible with the response time of the detector. With the detector at some distance from the image plane of the microscope, each object resolution element is encoded as a temporally modulated Fresnel pattern. The time series recorded at each CCD pixel thus contain the amplitude and phase information of the digital hologram. In practice, just a few frames are sufficient to extract this information using temporal heterodyning or frequency-space filtering.

The use of a local reference beam makes it possible to relax the coherence requirement, as was already achieved by Gabor in his first experimental demonstration of holography using a Mercury light source. In addition, recording the hologram in the time domain eliminates the problems associated with the twin images as well as the high spatial bandwidth requirement. Indeed, the detector bandwidth needed to record a hologram is not larger than that required to capture a single image of the specimen.

The reconstruction of a chosen focal plane through the specimen is done by digital correlation with a reconstruction function matched to that particular focal distance. Both the transverse and the axial resolution of the reconstructed image are identical to those of an image obtained directly through the microscope equipped with the same objective: with, of course, the obvious advantage that the hologram contains the entire volume information of the specimen. An example of 3D information extraction is shown in Figure 2. Since the entire complex wavefront information is recorded in the holo-

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Matter-wave interference of Fullerenes

The wave property of matter was postulated by Louis de Broglie[1] in the early days of quantum mechanics, and soon thereafter demonstrated for electrons by Davisson and Germer.[2] Since then, interference phenomena have been observed with neutrons, atoms and small molecules. Wave-particle duality opens up many philosophical question and becomes the more intriguing the bigger the objects are, but the quantum physics of mesoscopic or even macroscopic systems remains, experimentally, a generally unexplored field. As a first step towards mesoscopic systems, our group in Vienna performed interference experiments with the Buckminster Fullerenes C_{60} and C_{70}.[3] C_{60} is formed by 60 carbon atoms and has the shape of a soccer ball, whereas C_{70} looks like an American football.

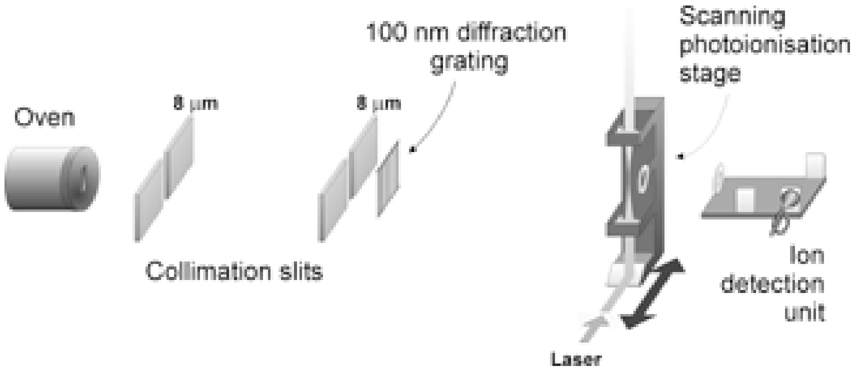

Figure 1. A schematic setup of the Fullerene interference experiment.

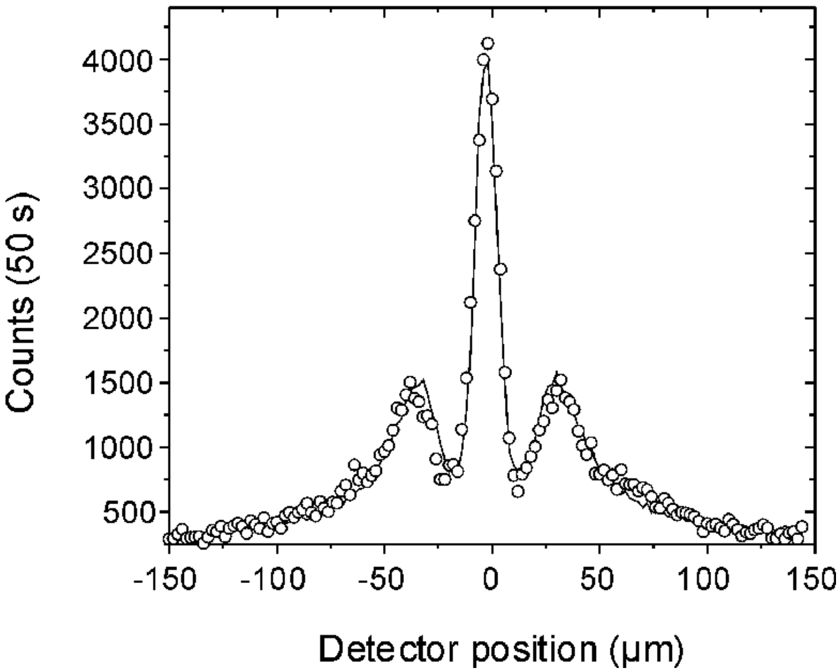

Figure 2. C_{60} interference pattern. The open circles represent the experimental data, the continuous line the theoretical expectation using standard wave theory.

Fullerenes turned out to be ideal candidates for our experiments because of their high symmetry. Fullerenes are also very stable, so that you can produce thermal molecular beams with them. On the other hand, they are very complex. In many respects they resemble—in their radiation properties, for instance—bulk materials, rather than the simple quantum mechanical systems we find in elementary particles.

Matter-wave experiments are conceptually simple: you guide a beam of particles onto a periodic structure, in our case it was a grating, and observe the interference pattern a certain distance from the structure with a detector. A schematic setup of our experiment is shown in Figure 1. An oven, heated to a temperature of approximately 900K, produces a thermal beam of the Fullerenes. The beam is collimated by two slits approximately 8µm wide, separated by 1m, and then directed towards a material grating made of SiN_x with a grating constant of 100nm. A meter or two away from the slits, we detect the Fullerenes by ionizing them with a tightly collimated argon-ion laser (with a beam waist of approximately 4µm, wavelengths mainly 488nm- and 514nm, and a power of approximately 25 W) and then count the ions. Only the Fullerenes that pass through the focus of the laser beam are ionized. An interference pattern can therefore be recorded by scanning the laser beam with micrometer resolution.

A typical interference pattern (in this case for C_{60}) is shown in Figure 2. Many velocity classes are present in the thermal beam—and therefore also a broad range of de Broglie wavelengths. The resulting limited longitudinal coherence is the main reason why we only see the first diffraction maximum. With a suitable velocity selection, the higher order maxima will also be visible. In our case, the most probable velocity is approximately 200m/s, corresponding to a de Broglie wavelength of 2.8pm, which is much smaller than the actual size of the Fullerenes which are approximately 1nm in diameter. With our experimental parameters (grating constant and distance between grating and detector) we expect the first order maximum in the detection plane at a distance of approximately 35µm from the zeroth order, in agreement with the experimental result.

Surprisingly, even for such complex and highly-internally-excited molecules as the Fullerenes, the effect of decoherence, i.e. the interaction of the quantum system with the environment, seems to be sufficiently weak to guarantee almost perfect coherence. The experimental data can be satisfactorily fitted without the assumption of any interference destructing mechanism. This encouraging result opens up the path to experiments with more complex molecules and, maybe one day, even with small viruses.

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Volume holograms for 3D spatial and spectral imaging

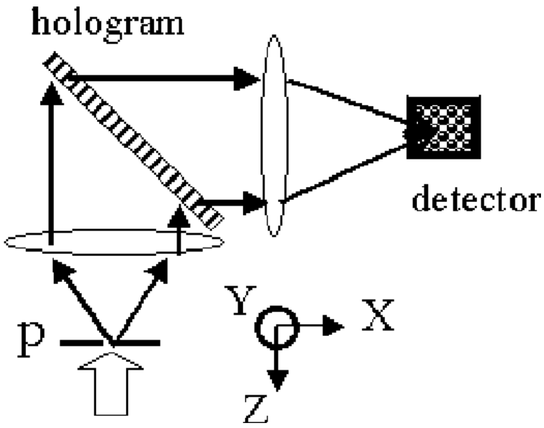

Figure 1. The holographic imaging system setup.

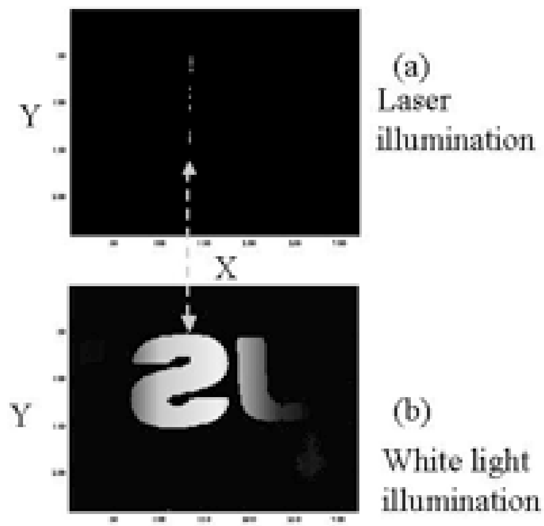

Figure 2. The 2D imaging properties of a single transmission hologram: (a) illuminating the 2D object with monochromatic source at the recording wavelength; (b) illuminating the 2D object with a white light source.

Volume holography has been primarily considered as a high-density data storage technology because of its high spatial and wavelength selectivities and because many holograms can be multiplexed in a given volume. However, these properties also make volume holography a powerful imaging tool. For instance, they can be used for the extraction and processing of a complex signal wavefront by acting as a color and spatial filter in confocal microscopes,[1] or acting as an element for the directly imaging of 3D spatial and color information.[2]

In the data storage application, a complex data signal wavefront is recorded inside the medium as sophisticated gratings through interference with a selective reference beam. It is then recovered later by the corresponding reconstruction beam. For the imaging application, on the other hand, simple pre-designed strong volume holograms are recorded to process information from unknown complex incident wavefronts. The high spatial and color selectivity of Bragg matching in volume holograms makes it possible to selectively extract specific information from the input and project it onto a detector. With multiple holograms within the same volume, it is possible to pull out individual holographic image elements (and their corresponding image information) by using different locations and wavelengths, thus providing multidimensional information without a scanning mechanism.

We have investigated theoretically, and demonstrated experimentally, a simple volume holographic system used for the direct imaging of the cross-sections of 3D chromatic objects, taken at different depths. Figure 1 shows the system concept, where a simple transmission hologram is recorded with a collimated beam from a point source on plane *p* and a planewave reference beam. This single hologram has the power to extract a 2D-slice color-filtered image due to the spatial and wavelength degeneracies of the volume hologram. When the hologram is readout with the same point source at the recording wavelength, the diffracted reference beam will be focused and will project a point image onto the photo sensor. If a 2D object is placed on plane *p* and illuminated with the same recording wavelength, the signal from a vertical line across the recording point source will be Bragg matched and projected into a corresponding vertical line image on the detector plane, as shown in Figure 2(a). This is due to the angle selectivity along the *x*-direction and the degeneracy along the *y*-direction. When it is illuminated by a polychromatic source, the different wavelengths Bragg match in the same hologram at different angles and project corresponding vertical color image lines onto the 2D image sensor. This regenerates the 2D object image in Figure 2(b) with a location-dependent colorfiltering effect.

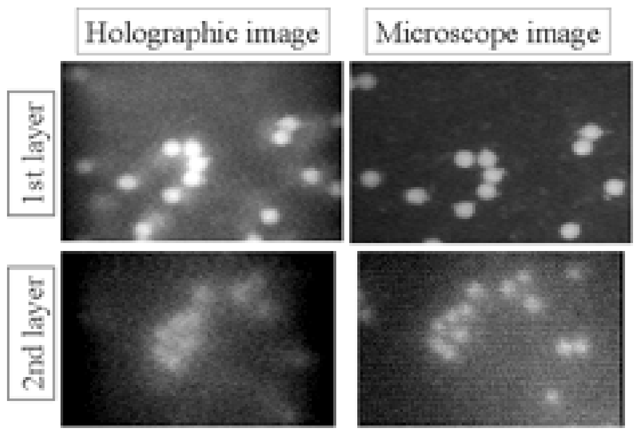

Figure 3. Holographic imaging of fluorescent microspheres (15µm diameter) and its comparison with direct microscope images.

When a 3D spatial chromatic object is placed around the plane *p*, the cross-section of plane *p* is Bragg matched and regenerated on the detector, with all other signals being Bragg mismatched. The sidelobe of the selectivity gives a limited background. With another hologram recorded by a different point source *p′*, a corresponding cross-section *p′* will be projected onto the 2D detector. Multiple holograms, corresponding to various cross-sections from 3D space and projecting into different reference directions, can be pre-recorded into the holographic medium. These are used to extract various cross-sectional images and project them into different detectors. In this way, 3D spatial information is projected into multiple 2D sensors and retrieved without scanning.

Figure 3 shows holographic imaging of fluorescent microspheres at different depths. The 15-micron diameter fluorescent beads are excited by a 488nm argon laserline and emit fluorescence with peak around 515nm. The two different holograms generate two cross-sectional images of the fluorescent beads at different depths. Also shown in Figure 3 are the direct microscopy images of the same florescent beads, scanned to get the same information.

The holographic imaging resolution depends on the imaging lens, volume holographic selectivity, and system architecture. The resolution along the degenerate *y*-direction is determined by the imaging system and the reso-

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Correlation fringes in TV-holography

TV-holography or Electronic Speckle Pattern Interferometry (ESPI) is a well-known, non-destructive whole-field technique for measuring displacements. It is based on television-camera recording of speckle interference patterns that provide correlation fringes, which can, for example, be further related to deformations or vibrations of a test object.[1]

The speckle correlation fringes in ESPI are usually obtained by the subtraction or addition of two speckle patterns. In the first mode, the speckle interferograms are recorded on separate frames and then are subtracted in a frame grabber. This operation eliminates most of the stationary optical noise, which facilitates the use of temporal phase-shifting techniques to automate data analysis. However, for standard CCD cameras the minimum time separation between exposures is approximately 16.7ms (for the RS-170 video format). Thus subtraction operation mode remains sensitive to environmental instabilities that occur between exposures.

This limitation can be overcome by using the addition operation with a double-cavity laser. In the double-pulse mode, the laser fires twin pulses with a very short pulse separation, around 19ns, within a single television frame and the double interferograms are added on the CCD camera sensor. However, the resultant addition correlation fringes contain stationary optical noise that reduces the fringe visibility and the signal-to-noise ratio.

To overcome this problem, some authors have proposed that fringes of improved visibility can be generated by subtracting two or more successive addition fringe patterns. However, as for the single-pulse subtraction mode, the proposed technique remains sensitive to environmental disturbances, although continuous updating subtraction schemes can be used successfully when the environmental disturbance develops slowly with respect to the television frame rate.

Leendertz described a photographic method to measure surface displacements by interfering two speckle patterns. There, a recording of a speckle pattern from an object was made upon a single frame of photographic film placed onto a rigid holder. After developing, the negative was returned to the holder, i.e. to its original position, and then any object deformation could be observed as live correlation fringes. This fringe-formation mechanism consisted of multiplying the transmittances of the film frame before and after the object deformation, that is, in using two speckle patterns. This technique formed the basis of early ESPI by replacing the photographic negative for a vidicon TV camera.

Electronic multiplication of the speckle patterns was not seen as feasible because multiplication fringes have the disadvantage of lower contrast and visibility than subtraction fringes obtained under normal illumination conditions. Also, multiplication fringes cannot be obtained within a single frame of a CCD camera, as can the addition fringes. However, the recent developments of liquid crystal displays will, perhaps, provide an alternative for obtaining multiplication fringes in real time.

We are currently researching new ways of correlating speckle patterns and analyzing the resulting correlation fringes. For instance, we have experimentally demonstrated the feasibility of obtaining multiplication ESPI fringes and proposed a digital filter to enhance its contrast.[2] We also proved that a local normalised variance digital filter is a useful tool for enhancing the contrast of addition and multiplication fringes in the configurations that uses smooth an speckle reference beams. And, in addition, we showed that the enhanced fringe patterns could be analyzed temporally or spatially to get the phase, regardless of whether or not closed fringes were present.[3]

Figures 1, 2 and 3 are subtraction, addition and multiplication fringes, respectively, obtained by adding, subtracting and multiplying two in-plane speckle patterns. The last two were enhanced with a variance filter as described in Reference 3. The noise is easily filtered, and the phase can be obtained, for example, by a Fourier method. If the fringes are closed, a phase-demodulation method based on Bayesian regularization theory is more suitable.[3]

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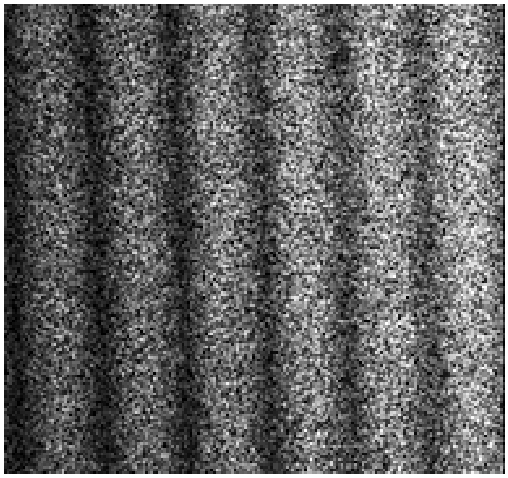

Figure 1. Subtraction fringes.

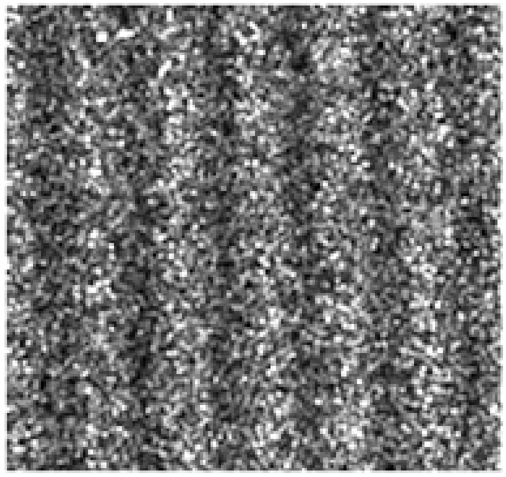

Figure 2. In-plane addition fringes enhanced with a variance filter.

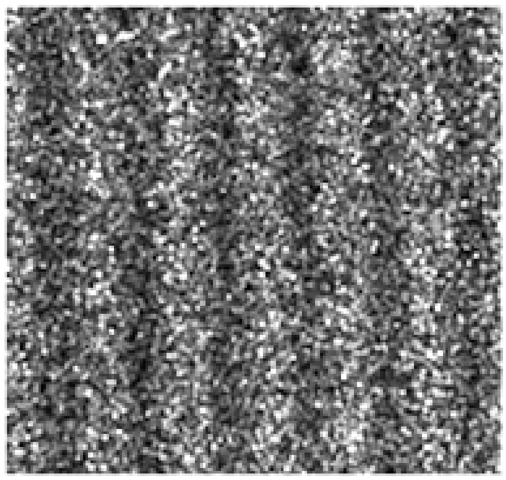

Figure 3. In-plane multiplication fringes enhanced with a variance filter.

Fiber Bragg Gratings: Holograms in time and frequency

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considered as holograms in which spectral and temporal information are encoded in the same fashion that conventional holograms encode spatial and angular information. This space-time duality allows researchers to implement the spectral-temporal equivalent of conventional holographic optical elements: as an example, a quadratic chirp will act as a spectral-temporal diffractive lens.

Going one step further, a whole plethora of optical signal processing architectures become transposable to the spectral-temporal domain, with potential applications in optical fiber communications. At Templex Technology, for example, we are encoding complex phase patterns that correspond to a family of orthogonal codes. A signal reflected by such a hologram acquires a complicated temporal and spectral pattern (Figure 1). If this signal is then directed to an FBG having the inverse transfer function, it will emerge in its original form upon reflection from the second fiber. Another signal not possessing the correct code will not be "reconstructed" in the proper fashion, and so will remain smeared. This matched filtering operation is the spectral-temporal equivalent of the well-known Vanderlugt filter. It can be used to efficiently complement DWDM by subdividing a wavelength channel into a number of sub-codes, a technique known as optical code division multiple access (O-CDMA). O-CDMA is also attractive for optical encryption given the proper choice of codes.

Fabrication

FBGs are fabricated by interfering UV light within the core of special purpose optical fibers. Boron and Germanium co-doped fibers, which are sensitive in the UV, are often used. It is also possible to dope ordinary SMF-28 fiber with hydrogen to render it photosensitive. This is achieved by placing the fiber in a high-pressure hydrogen chamber for a few days. Higher refractive index modulations ($>10^{-3}$) are attainable with hydrogen loading than with co-doped fiber.

Multiple methods can be used to write FBGs. The simplest and most commonly used technique is a simple contact copy in which a mask, determined by the desired phase profile, is placed in close proximity to the fiber and then exposed to UV light. This method is relatively simple and robust, and works well with poorly coherent sources like excimer lasers. It is, unfortunately, relatively inflexible due to the need to fabricate a new phase mask for each different FBG. Interferometric techniques that use mirrors and/or combinations of mirrors and phase masks are more flexible, but generally require higher coherence sources such as frequency-doubled argon lasers. In some implementations a phase pattern is scanned across the fiber to generate a synthetic aperture of arbitrary length.

Although the fabrication of FBGs is relatively simple in theory, they can be devilishly difficult to make because phase coherence needs to be maintained along the entire length of the grating. Like display holography, FBG manufacture is an art as well as a science, with jealously guarded tricks of the trade. Let's just say that making FBGs requires a great deal of patience, an almost maniacal attention to detail, impeccable technique, and a great deal of determination: just like display holography. It thus naturally appeals to the same type of individual.

This article has barely scratched the surface of the rich physics and engineering inherent in the design and fabrication of fiber Bragg gratings. There is no doubt that new applications in sensing and fiber communications will emerge as our ability to manufacture very complex phase and amplitude profile gratings improves, and as we get a better understanding of the underlying physical processes. For a general reference, the reader can consult two recently published textbooks.[1,2] Some of our more recent work on O-CDMA has been published at the 2001 Optical Fiber Conference.[3]

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Volume holograms for 3D spatial and spectral imaging

continued from p. 6

lution along the horizontal *x*-direction depends on the angle and wavelength selectivity due to their coupling. The depth selectivity is determined by the numerical aperture of the collimating lens and the thickness of the volume hologram. The 2D imaging takes advantage of the wavelength degeneracy, which makes it possible to extract further color information by using holograms recorded with various wavelengths. On the other hand, due to the Bragg matching of only a specific wavelength at corresponding location, the light efficiency for the spatial image is limited by the color bandwidth of wavelength selectivity.

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Spatiotemporal digital microholography

continued from p. 4

gram, all the operations which are so useful in biomedical imaging, e.g., phase contrast, dark field, Nomarski interference contrast, etc., can be performed *a posteriori* and at will on the recorded holographic data. An illustration of these capabilities is shown in Figure 3.

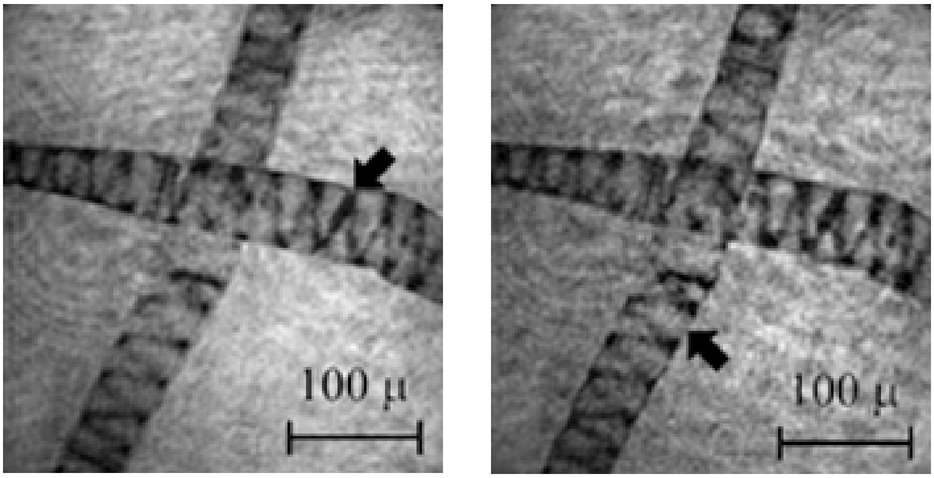

Figure 2. Two sections of a spyrogira algae specimen, about 25µm apart, reconstructed from a digital hologram obtained with a 20× objective (effective numerical aperture, 0.25) on a 504×485 pixel CCD sensor. The exposure time was about 25 frames at 30 frames per second.

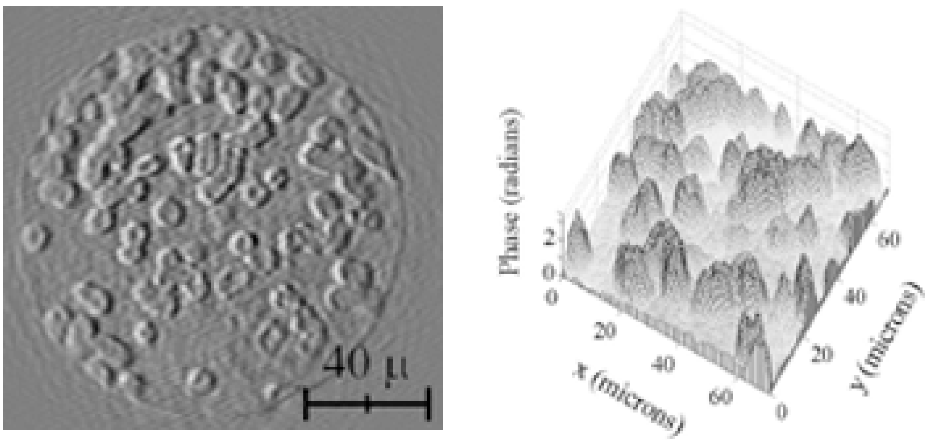

Figure 3. a) Blood sample reconstructed from a hologram recorded with a 40× objective (effective numerical aperture 0.45). Nomarski interference contrast was applied a posteriori to the holographic data. b) Phase map of the same blood sample as in (a), obtained from the same holographic data, but using a posteriori quantitative phase contrast.

Conclusion

Recent advances in solid state detectors with high spatial and temporal resolutions allow a new approach to old holographic and interferometric imaging methods: the advantages of which have not been fully realized yet. We have shown here a few examples in which most of the problems of conventional holographic microscopy could be overcome by using time as an additional dimension. We have also explored its use in, for example, low coherence interferometric imaging,[11] optical sectioning, and imaging through scattering media,[12] among many other possible applications.

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Holographic velocimetry

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combined to form a single, volumetric, 3D vector map, as shown in Figure 2. There are several important consequences of using image correlation analysis. Image correlation does not require image matching on a particle-by-particle basis, nor does it attempt to track particles in three dimensions. Provided that the concentration of particles is high enough, each interrogation cell yields a displacement vector measurement, and the vectors can be evaluated on a uniform, non-random grid.

The third method of hologram interrogation uses complex-correlation of the particle field. In the two methods described previously, sharply focussed images were used in the interrogation. Since only the image intensity was measured, the phase information from the hologram image was discarded. In contrast, complex-field correlation uses both the amplitude and phase of the reconstructed particle field, and does not depend on sharp images. As a result, complex-field correlation is inherently tolerant of phase aberrations. Recently, my colleagues and I have successfully implemented a complex-field correlation technique, called "object-conjugate" reconstruction.[5-10] Rather than looking at the particle images themselves, as in HPIV, this system samples the interference fringes found in the spatial power-spectrum of the two displaced image fields. Unlike the two-dimensional intensity correlation of HPIV, which requires stereoscopic vector synthesis to obtain 3D results, complex-field correlation inherently measures three-dimensional displacement.

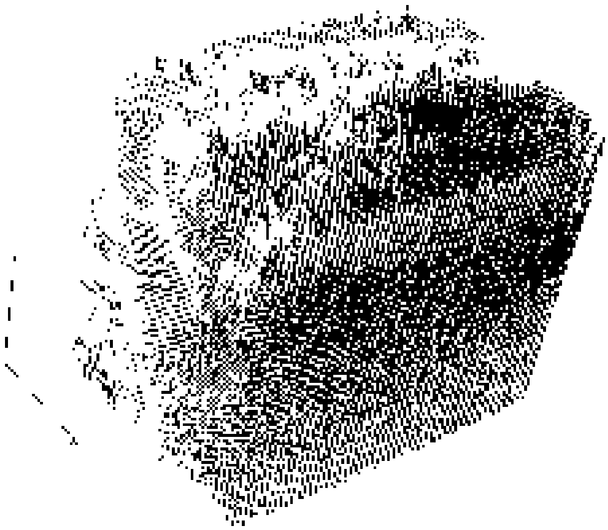

Figure 2. The 3D velocity-field volume showing the same jet-flow vortex entrainment arm as depicted in Figure 1. This result was composed from more than fifty 2D velocity maps in stereo.

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Holography

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Holographic velocimetry

Holographic velocimetry (HV) is the only experimental method capable of measuring the instantaneous, three-dimensional velocity field in a flow at millions of points in a volume simultaneously. The task of holographic velocimetry is to follow the movement of millions of micron-sized particles suspended in a flow between two or more instants in time. These neutral-buoyant "seed" particles are carried by the flow while acting as point sources that scatter the light and enable us to image the flow movement. By examining the holographic image of each particle from two viewpoints, in principle, we can triangulate on the three-dimensional particle positions at each time instant. Finally, by measuring every particle displacement between two snapshots, and by knowing the time interval between exposures, we can determine the quantitative, three-dimensional velocity field. The biggest challenge in HV is to automate this into a process that is fast, accurate, and roboust.

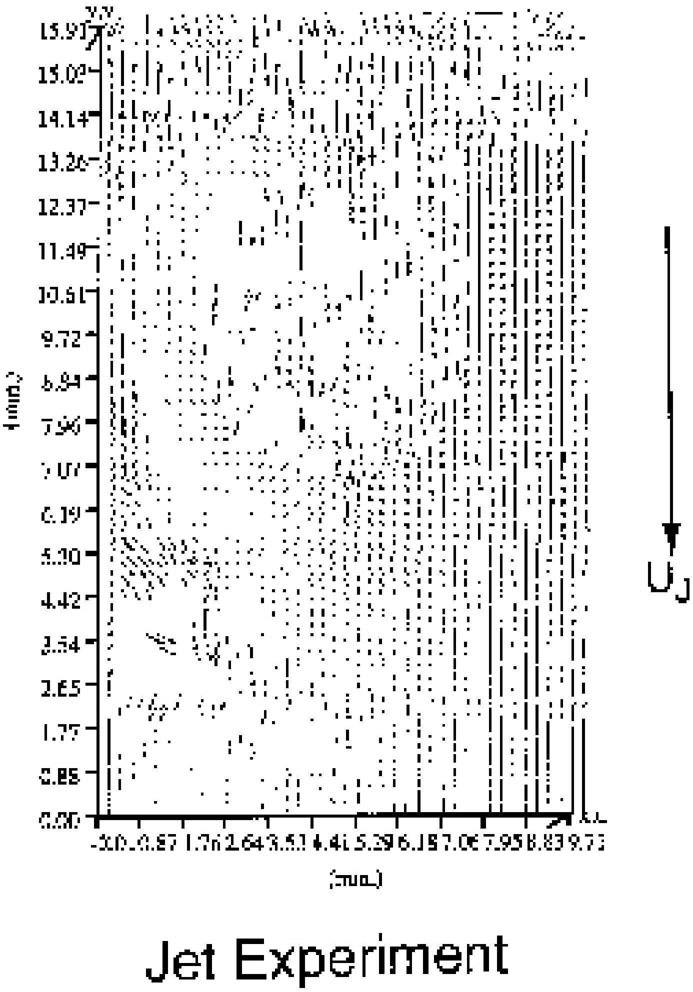

Figure 1. A 2D velocity map that shows the close-up of a vortex entrainment arm from a jet flow experiment in air that is seeded with submicron oil droplets.

Unscathed by the recent movement by experimentalists, *en masse,* toward direct digital recording, the large space-bandwidth requirements of holographic velocimetry necessitate a physical recording medium such as silver halide. In this respect, HV remains one of the last bastions for traditional photographic recording in optical metrology. In spite of its "inconvenient" wet-process methods, HV is uniquely useful in the study of unsteady flow phenomena and as a means of validating computational models in fluid mechanics. Ironically, as a technique, holographic velocimetry has barely escaped its infancy in spite of of a developmental history over 35 years long. In this regard, HV has progressed remarkably slowly as a field. While much of this can be attributed to the absence, until recently, of cost-effective, high-speed computer and image processing, it has also been due to the need for further development in the basic HV measurement process itself.

While many experimental forms of HV currently exist, two basic process steps are always involved: (1) holographic recording and (2) hologram "interrogation" analysis. Depending on the experimental requirements, nearly any hologram recording geometry can be employed with HV. Principally, however, there are three competing hologram interrogation methods. The first interrogation method is known as "particle tracking", which attempts to individually follow the three-dimensional movement of every particle between the reconstructed time frames. Unfortunately, because particles are randomly placed and one particle looks much the same as every other, such simultaneous, automated tracking of millions of particles between multiple time frames has only recently become viable.[1,2]

The second interrogation method is based on intensity correlation analysis of particle image groups. This approach, known as holographic particle image velocimetry (HPIV), has evolved from the established technique of particle image velocimetry (PIV).[3] In HPIV, the holographic image volume is broken into a stack of two-dimensional slices that are digitized separately with a CCD camera.[4] Each digitized slice is then partitioned into separate image cells for correlation and analysis, and the correlated results from each cell are combined to produce a two-dimensional vector map of the flow, as shown in Figure 1. After a stack of 2D vector maps has been constructed in this fashion, the hologram is analyzed a second time from a second viewing direction to produce a second set of 2D vector maps. Finally, these stereo 2D data sets are

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