# Very thick holographic nonspatial filtering of laser beams

**Jacques E. Ludman,** MEMBER SPIE
**Juanita R. Riccobono**
Northeast Photosciences, Inc.
18 Flagg Rd.
Hollis, New Hampshire 03049
E-mail: 71053.3526@compuserve.com

**Nadya O. Reinhand**
Machinery Sciences Institute
V.O. Bolshay, pr. 61
St. Petersburg, Russia 199178

**Irina V. Semenova**
A.F. Ioffe Physical Technical Institute
Polytechnicheskaya ul. 26
St. Petersburg, Russia 194021

**Yuri L. Korzinin**
S.I. Vavilov State Optical Institute
St. Petersburg, Russia 199174

**Selim M. Shahriar**
Massachusetts Institute of Technology
Cambridge, Massachusetts 02139

**H. John Caulfield,** FELLOW SPIE
Fisk University
Department of Physics
Nashville, Tennessee 37208

**Jean-Marc Fournier,** MEMBER SPIE
Rowland Institute
100 Edwin Lan Blvd.
Cambridge, Massachusetts 02142

**Philip Hemmer,** MEMBER SPIE
Rome Laboratory
RL/EROP, 63 Scott Road
Hanscom Air Force Base, Massachusetts 01731

**Abstract.** A novel device, the nonspatial filter, is described for laser beam cleanup. It is based on the Bragg selectivity of thick holograms. Unlike pinhole and fiber spatial filters, which employ lenses and apertures in the transform plane, nonspatial filters operate directly on the laser beam. This eliminates the need for laser beam focusing, which is the source of many of the material and alignment instabilities and laser power limitations of spatial filters. Standard holographic materials are not suitable for this application because differential shrinkage during processing limits the maximum Bragg angle selectivity attainable, and because they are generally too thin. New technologies that eliminate the problem of differential shrinkage are described. These technologies are based either on the use of a rigid porous substrate material, such as porous glass, filled with a light-sensitive material, such as holographic photopolymers or dichromated gelatin, or on the use of a thick photopolymer with diffusion amplification (PDA). We report results of holographic nonspatial filtering of a laser beam in one dimension, with an angular selectivity of better than 1 mrad.  [S0091-3286(97)01606-1]

Subject terms: holography; lasers; spatial filtering.

Paper 14017 received Jan. 13, 1997; accepted for publication Jan. 14, 1997.

## 1 Introduction

The laser owes much of its usefulness to its inherent high degree of spectral purity and spatial uniformity. This spectral purity, however, also produces a large coherence length, which makes laser light very sensitive to the spatial imperfections (such as dirt and scratches) present in most optical components, including the laser optics themselves.

Spatial nonuniformities can seriously degrade the signal-to-noise ratio (SNR) of laser-based sensing systems. For example, a high-resolution image can lose information if the input laser beam has an intensity minimum at a critical feature location. It is also possible for the laser light to introduce erroneous information due to the inability to distinguish whether a particular intensity variation is produced by the image or by a laser beam imperfection. Aside from SNR degradation, spatial imperfections in laser beams degrade the accuracy of power delivery in high-power applications and the effective pointing stability in low-power systems.

Clearly, for practically any application, the input laser beam should be as clean as possible. Currently this is accomplished by spatial filtering.[1] There are two types of spatial filters in widespread use. The most common is the so-called ''pinhole'' filter, which consists of a lens with a pinhole in the focal plane. For more demanding applications, the pinhole is replaced by a single-mode optical fiber. The problem with both types of spatial filters is the requirement for matching spatially and angularly a tightly focused laser beam to a small target. This problem is aggravated by the fact that positioning is three dimensional, since tightly focused laser beams have short Rayleigh lengths. Experimentally, the initial alignment (or realignment) of spatial filters is difficult and tedious and requires a manual search through 3-D position space in an attempt to maximize the throughput intensity. Furthermore, maintaining proper alignment is often a problem.

Moreover, the focusing required for both pinhole and fiber spatial filters are problematic when used with high-power lasers. A high-power laser can damage a pinhole or even create a new one. They are usually aligned with the power turned down. If the pinhole position changes or if there is a slight misalignment, a high-power laser can damage the pinhole or damage the edges when the power is increased. Fibers have many of these problems and in addition have other unique ones in that the focused energy can produce nonlinear optical interactions (e.g., in Brillouin and Raman scattering) and index changes, or even permanent damage due to heating. Because these devices are in the focal plane of the converging lens, there are problems due to reflections that are, by definition, reflected back into the laser itself, occasionally with disastrous effects.

To solve the numerous problems inherent in spatial filters, we have developed nonspatial filtering.[2–4] The basic idea of nonspatial filtering is similar to spatial filtering. In spatial filters, since a laser beam with arbitrary spatial variations in intensity can be expressed as linear combinations of plane waves, a Fourier transform lens is used to convert the propagation angle into position. The pinhole then selects the spatial on-axis component and blocks the others. In contrast, nonspatial filtering is done directly on the laser beam propagation angle. A holographic filter element is inserted in the laser beam path to selectively diffract light propagating at a particular on-axis angle, and transmit without diffraction the unwanted light (to be discarded, but not reflected back into the laser or absorbed by the filter). In particular, we use a very thick hologram as the filter element. The Bragg selectivity of such a hologram guarantees that only waves propagating at a particular angle (namely, the Bragg angle) are diffracted and deflected. Two-dimensional filtering can be achieved by using two such holograms in series. Since the nonspatial filter operates with an unfocused beam and relies on Bragg selectivity to remove excess or arbitrary spatial variations in intensity, the majority of the problems due to focusing are alleviated.

Standard holographic materials are not suitable for this application because differential shrinkage during holographic processing limits the maximum Bragg angle selectivity attainable by affecting the Bragg angle in a nonuniform manner. What is needed is a holographic structure with negligible differential shrinkage during processing. This paper reports on such holographic structures and their performance as nonspatial filters.

## 2 Theory

The theory of wave propagation in thick hologram is well known.[5,6] For simplicity, we consider here the special case of no absorption with only phase modulation due to the presence of index modulation. For a monochromatic hologram with a grating periodicity of $\Lambda$, the angle of incidence $\theta_b$ for a perfectly phase matched Bragg diffraction is given by

$$\cos\,(\theta_b) = \frac{\lambda}{2n\Lambda}.$$

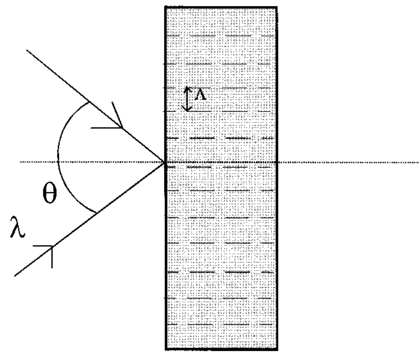



**Fig. 1** Setup scheme for hologram recording with symmetric incident laser beams. The optimum playback is at 90-deg diffraction ($\theta_0$ = 45 deg) so the fabrication $\theta_0$ must be chosen to take account of any wavelength difference between recording and playback.

Here, the angle of incidence $\theta_b$ is the angle between the incident ray and the holographic fringes within the media. Also, $\lambda$ is the wavelength of incident light, and $n$ is the average index of refraction of the hologram. Here we assume that the hologram fringes are perpendicular to the surface of the hologram. In this case, $\theta_b$ is related to $q$ in Fig. 1 by Snell's law ($\sin\theta/2 = n * \sin\,\theta_b$). The diffraction efficiency, $\eta$, is then given by

$$\eta = \sin^2\left(\frac{\pi n_1 d}{\lambda\,\cos\,\theta_b}\right).$$

Here, $n_1$ is the amplitude of the sinusoidal index modulation, and $d$ is the thickness of the hologram. The smallest value of $n_1$ for which maximum diffraction can be obtained varies inversely with the thickness, and is very small for very thick holograms. The full width at half maximum (FWHM) of the angular selectivity is given by[5]

$$\delta\vartheta_{\mathrm{FWHM}} \cong \frac{\lambda}{d}.$$

For the typical angular deviation used in the nonspatial filter ($\theta \approx 45$ deg) the beam deviation is approximately 90 deg, and for such substantial deviations the relative angular selectivity and wavelength selectivity are similar.[6] For a 1-mrad beam cleanup filter, the wavelength sensitivity would also be $10^{-3}$. Laser linewidths are several orders of magnitude narrower than this and are not differentiated by the filter. For high wavelength sensitivity, if desired, the deviation must be close to 180 deg (reflective geometry). The highest angular and lowest wavelength selectivity occur for small angle deviations, but practical considerations lead to the choice of a larger angle.

## 3 Thick Recording Media

As a result of the theoretical analysis (see Sec. 2 and Ref. 3), we determined that a holographic grating to be used as a nonspatial filter with an angular half width selectivity of 0.5 to 2 mrad, should be 0.5 to 2 mm thick and should have a spatial frequency approaching 3500 $\mathrm{mm}^{-1}$. For high-efficiency holograms, this medium must have a refractive index modulation of about 1 to $4\times10^{-4}$. Such 3-D gratings can be recorded in thick recording media using impregnated porous glasses[7] and also on photopolymers with diffusion amplification[8] (PDA). By comparison, a 40 × objective with a 5-$\mu m$ pinhole yields angular selectivity of approximately 1 mrad.

The porous volume recording media are based on a rigid silicate porous matrix filled with a photosensitive material. The photosensitive material is introduced into the pores inside this porous matrix, but it covers only the surface of these interconnected pores. This composite material forms a continuous capillary network that conveniently provides a network for reagent penetration inside the specimen during the processing of the hologram. The completed device is then a composite material (porous glass and processed photosensitive material) with the desired index modulation.

The requirements of the system are mechanical rigidity, fairly large free volume of internal pores, and pore size less than the recording and playback wavelengths. These porous glasses have a free volume of connected pores equal to 0.15 to 0.35 $cm^3/g$ with a specific surface of 100 to 300 $m^2/g$ and a cavity pore diameter of about 10 to 30 nm. This is ample for holographic recording and playback with a low level of light scattering.

Another useful thick medium is PDA consisting of polymethylmethacrylate (PMMA) with included photochromic quinone molecules. The reaction of the phenantrenquinone photoreconstruction in PMMA leads to the formation of phenantrenic structures associated with polymers. As a result, during recording, two opposite phase gratings are produced. During postexposure processing (thermal treatment) the free quinone molecules are redistributed uniformly, which removes one of the phase gratings and thus increases substantially the holographic efficiency. This redistribution leads to the disappearance of one of the opposite phase gratings and, thus, to a considerable increase of the hologram diffraction efficiency.

## 4 Experiment

### 4.1 *Hologram Recording and Evaluation*

The recording geometry for both the porous material and PDA is simply the interference of two collimated coherent beams (single-mode argon 488 or 514 nm) directed toward the holographic material at 45 deg to the normal and 90 deg to each other, as shown in Fig. 1. This results in fringes perpendicular to the holographic surface and to an optimum angle for playback at nearby wavelengths. In playback, a signal beam is filtered to a small angular divergence with all laser light outside of this central on-axis light simply continuing on directly through the hologram. This filter cleans up in one dimension. The second dimension requires another hologram with a grating at right angles to this one.

Holograms can be recorded at any combination of incident angles so that on playback they are suitable for virtually any wavelength from 300 nm to as long as wavelength as the substrate is transparent. They can be fabricated at one wavelength for playback at another or for simultaneous multiwavelength playback with slightly different diffraction efficiencies for different wavelengths.

For high-quality recording and the evaluation of gratings with high angular selectivity the following conditions must be ensured:

1. There are negligible nonuniformities in the laser beam that would lead to spatial exposure variations.
2. The angular deviations in parts of the exposure beam are less than the desired angular selectivity. The recording beam must be better than the eventual clean laser beam in use.
3. The filter surfaces must be carefully index matched, because of the porous structure of the surface.
4. The structure must be mounted carefully during recording and during measurement to avoid even slight deformation of the substrate.

An ideal method for measuring the holograms is to use a well-collimated beam and measure and record the angles and efficiencies of the holograms in small areas and thus map the entire area. Problems inadvertently introduced (i.e., 1 to 3, just listed) can be identified in this way.

The angular selectivity profile was obtained by means of intensity measurements in the hologram zero order, while the hologram is rotated (the intensity detector does not move). It is simpler to measure the undiffracted light as the hologram is rotated than to track and measure the diffracted beam.

### 4.2 *Experimental Results*

We performed a series of experiments to fabricate highly selective holographic elements in porous glasses and also in PDA.

We previously reported[3] results on the complete testing of holograms recorded in a porous material to find an optimal combination of recording parameters (specimen thickness, spatial frequency, exposure) resulting in the fabrication of a highly selective and highly efficient nonspatial filter. Here we have achieved values of the refractive index modulation of the order of $\sim10^{-3}$, which is sufficient for holograms (0.5 to 2 mm thick) with diffraction efficiency approaching 100%. Holograms 2 mm thick yield filters with an angular selectivity contour of 0.5 mrad.

To study the resolution ability of the materials, a series of holograms with different spatial frequencies and equal exposures were recorded. The amplitude of refractive index modulation was calculated based on the measurements of hologram diffraction efficiency. Suitable refractive index modulation was obtained with increasing grating spatial frequency up to 3400 $mm^{-1}$ (see Fig. 2).

Figure 3 represents the experimental and calculated values of the angular selectivity contour for different spatial frequencies of the holographic element ($T = 0.7$ and $\lambda=0.488$ $\mu$m, where $T$ is the hologram thickness and $\lambda$ is the recording wavelength). One can see that experimental angular selectivity is good, but not as good (low) as predicted. There is a clear relationship[4] between nonuniform index modulation and the angular selectivity contour. There are at least two sources of index modulation nonuniformity. They are variable exposure, either due to beam inhomogeneities or due to beam absorption in the hologram during exposure, and nonuniformities in the absorption by the po-

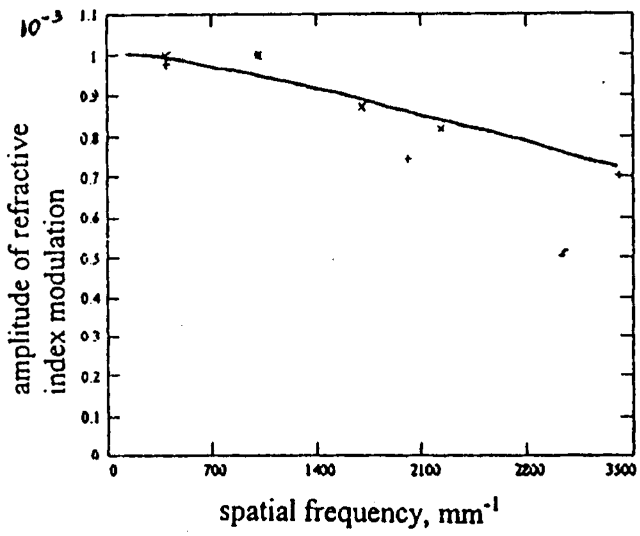



**Fig. 2** Experimental results and the amplitude of the refractive index modulation versus spatial frequency for the porous material.

rous media of both the photosensitive media and the processing agents. Nonuniformity changes and usually widens the angular selectivity contour.

To analyze and compare selective features of holograms recorded in porous materials and PDA we prepared specimens of the same thickness (1.8 mm) and recorded holographic gratings with the same spatial frequency ($2200\ \mathrm{mm}^{-1}$).

Figures 4(a) and 4(b) present the measured contours of angular selectivity for these two materials. Figure 4(c) displays the theoretical[5,6] angular selectivity contour for this grating (assuming uniform sinusoidal index modulation). As can be seen, the half width of the experimental contours

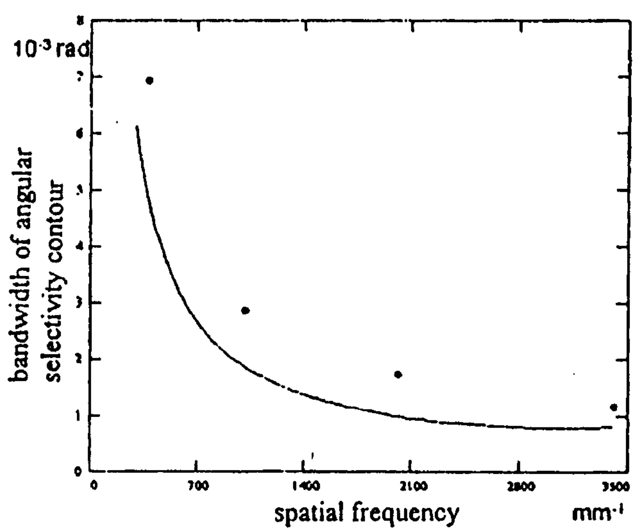



**Fig. 3** Bandwidth of the angular selectivity contour versus spatial frequency of the grating in the porous material. The solid line represents the calculated data, and the points indicate the experimental data; $T=1$ mm and $\lambda=0.488$ mkm.

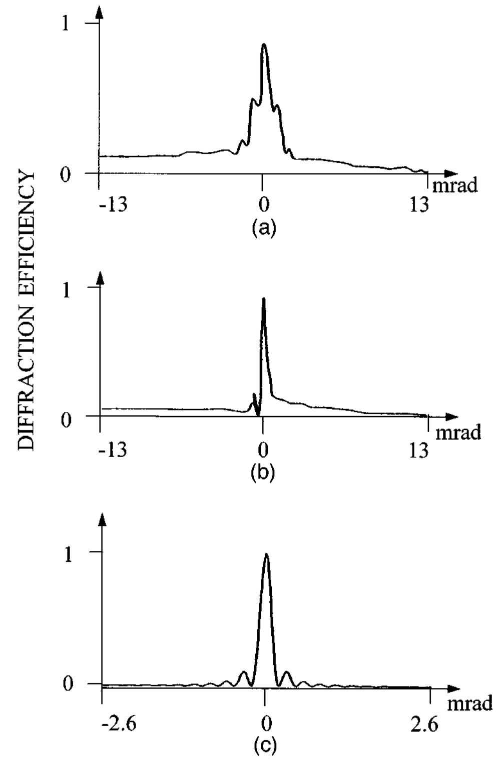



**Fig. 4** Contours of angular selectivity for holograms recorded (a) in the porous glass and (b) in PDA. Both specimens have the same thickness (1.8 mm) and the same spatial frequency ($2200\ \mathrm{mm}^{-1}$). (c) Theoretical contour calculated for the same parameters of the hologram.

of angular selectivity of the 3-D grating are some what greater than the theory: the bandwidth of the theoretical contour is $2.15\times10^{-4}$ rad, that for porous material is $8\times10^{-4}$ rad, and that for PDA is $5\times10^{-4}$ rad. A part of this difference is not real (due to the filter) but is due to the angular divergence of the test laser ($3\times10^{-4}$ rad).

Previously[4] we analyzed the relationship between the angular selectivity contour and the index modulation nonuniformity character. The result for a porous hologram [as presented in Fig. 4(a)] is that the two large sidelobes are to be expected if the index modulation is relatively high at the top and bottom surfaces and low in the middle of the filter. This is consistent with the diffusion of the photosensitive material and the processing reagents through the two surfaces. The index modulation is higher near the surfaces, and lower in the middle. The PDA clearly does not have such sidelobes.

One can change the shape of the angular selectivity contour by changing the preparation procedure of the porous photosensitive material. For instance, a grating with a maximum index modulation in the filter center would have a smooth contour of angular selectivity without lateral maxima.[4]

Figure 5 shows the result of a beam cleanup in one dimension. The beam was a Gaussian HeNe and the filter was not index matched. The profile of the transmitted (or input) beam is shown in Fig. 6. The profile can be cleaned up in the other direction with a second filter.

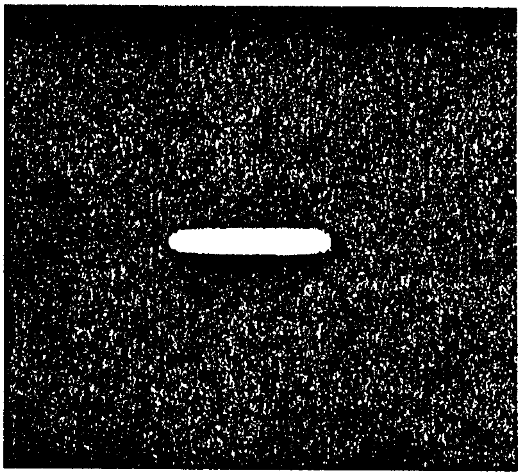


**Fig. 5** Profile of the diffracted beam, showing nonspatial filtering in the vertical direction. Light above and below the angularly selected filtered beam is not diffracted. This is the profile after filtering.

The holographic laser filter described here is currently a 1-D, viable device. The future direction of this work will be first to use two crossed nonspatial filters to completely filter a laser beam. A single filter with, for example, vertical fringes filters the laser beam in the horizontal direction. A second filter with horizontal fringes will diffract vertically and complete the laser filtering. It is clear that in many ways this device will function better than the spatial filters it replaces (pinholes and optical fibers). Besides being simpler and easier to operate than previous systems, it avoids many of the substantive, fundamental problems of spatial filters in high-power or high-energy laser beam cleanup, as pointed out in the introduction.

Two of these filters properly oriented proved capable of cleaning the beam in both the horizontal and vertical directions. For each filter, only one adjustment is necessary, as each hologram is quite insensitive to the angle orthogonal to the one to which it is supersensitive. Untrained workers learned within minutes how to establish alignment within seconds; that is, a hologram alignment is much simpler than pinhole alignment. The output beam is deviated from the input beam, but (essentially by definition, since two intersecting straight lines define a plane) in the same plane. Details of the mounting and adjustment will be presented in another paper.

In addition to the advantages of this new technology in comparison with conventional techniques, there are some additional features that are unique to the holographic filter. The primary one is the fact that the amplitude of the index modulation can be varied as a function of the depth of the filter. Such variations lead to modifications of the angular selectivity profile. The output laser beam can have a contour as well as an angular divergence, as required. Additional benefits of this technology are that the output can be tailored in shape as well. The output beam can be designed to be parallel, diverging, or even converging. Other potential applications include use as an étalon and as a Raman filter or for spectroscopic analysis.

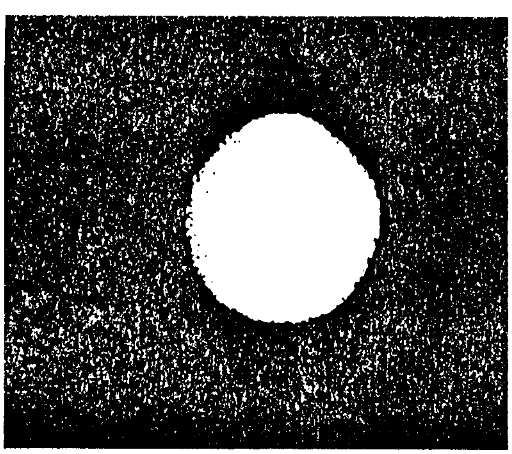


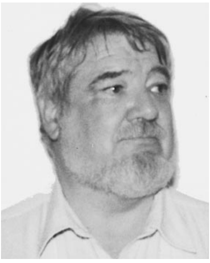
**Fig. 6** Profile of the incident beam before filtering (identical to transmitted beam).

## *Acknowledgments*

Northeast Photosciences was supported by the Ballistic Missile Defense Organization (BMDO) under a high-risk Small Business Technology Transfer (STTR) program managed by the Army Space and Strategic Defense Command (SSDC) (Richard Gerr). Reinhand and Semenova were supported by the European Office of Aerospace Research & Development (EOARD). This work originated at the sixth Annual Piermont Place Conference in 1986. H. J. Caulfield's work was sponsored in part by the Air Force Office of Scientific Research.

## *References*

1. E. Hecht and A. Zagac, *Optics*, Addision-Wesley, Reading, MA (1975).
2. J. Ludman, J. Riccobono, J. Caulfield, J. M. Fournier, I. Semenova, N. Reinhand, and P. Hemmer, ''Porous-matrix holography for nonspatial filtering of lasers,'' in *IS&T/SPIE Symp. on Electronic Imaging: Science and Technology, Proc. SPIE* **2406**, 76–85 (1995).
3. J. E. Ludman, J. Riccobono, N. Reinhand, Y. Korzinin, I. Semenova, and S. Shahriar, ''Nonspatial filter for laser beams,'' presented at *8th Laser Optics Conf.* June 27–July 1, 1995, St. Petersburg, Russia.
4. J. E. Ludman, J. Riccobono, N. Reinhand, I. Semenova, Y. Korzinin, and S. Shahriar, ''Holographic nonspatial filter,'' *Proc. SPIE* **2532**, 481–490 (1995).
5. H. Kogelnik, ''Coupled waves theory for thick hologram gratings,'' *Bell Syst. Tech. J.* **48**, 2909–2947 (1969).
6. J. E. Ludman, ''Approximate bandwidth and diffraction efficiency in thick holograms,'' *Am. J. Phys.* **50**, 246 (1982).
7. S. A. Kuchinskii, V. I. Sukhanov, and M. V. Khazova, ''Principles of hologram formation in capillary composites,'' *Opt. Spectrosc.* **72**(3), 716–730 (1992).
8. A. V. Veniaminov, V. F. Goncharov, and A. P. Popov, ''Hologram amplification due to diffusion destruction of opposite phase structures,'' *Opt. Spectrosc.* **70**(4), 864–869 (1991).

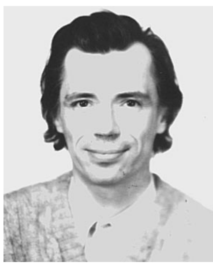


**Jacques E. Ludman** received a BS from Middlebury College in 1956 and a PhD from Northeastern University in 1973. He was a research scientist at U.S. Air Force Rome Air Development Center, Hanscom Air Force Base, Massachusetts, from 1957 until 1977, and chief of the Optical Signal Processing Section there from 1978 to 1987. He was a visisting scientist at Centre National d'Etudie de Telecommunication, Lanion, France, from 1977 to 1978, and a visiting scientist at MIT from 1987 to 1988. He is president of Northeast Photosciences, Inc., a fellow of the American Optical Society, and a member of SPIE and of Sigma Xi.

**Juanita R. Riccobono** is a chemistry faculty member at the University of Texas, Brownsville. Before joining the university, she worked as a senior scientist and a project manager at Northeast Photosciences in Hollis, New Hampshire. She holds a BA in chemistry from Northwestern University and a MS in energy engineering from the University of Massachusetts at Lowell. She is a member of the Sigma Xi Research Society and American and International Solar Energy Societies and is listed in Who's Who in Science and Engineering.

**Nadya O. Reinhand** graduated from the Optical Department of State University, St. Petersburg, Russia, in 1984. She received her PhD in the field of physics and mathematics in 1990 at State University, St. Petersburg. Since that time she has worked at the Institute of Mechanical Engineering Problems of the Russian Academy of Sciences. She has been Vice-Director of this institute for the past two years. She is known for her work in the fields of laser optics, diffraction elements, holography, and nondestructive testing. She is the author of 35 papers, among them 5 certified inventions. She was the member of organizing committees of several international conferences.

**Irina V. Semenova:** Biography not available



**Yuri L. Korzinin** graduated from St. Petersburg State University, Physical Department in 1980. He received his PhD in 1988. He is now the leading scientist at Vavilov State Optical Institute, St. Petersburg, Russia. He is the author of more than 30 scientific papers. His fields of interest include holographic optical elements, theoretical investigation of three-dimensional hologram properties, and photosensitive materials for three-dimensional holography.

**Selim M. Shahriar** received a BS in physics in 1986, and a BS, MS, and PhD in electrical engineering from the Massachusetts Institute of Technology, Cambridge, in 1986, 1989, and 1992, respectively. His research activities include optical data storage in three, four, and five dimensions; optical phase conjugation using two-photon resonant media; generation of squeezed states of light for faint image detection; atomic clocks using Bose condensates; and nanolithography using atom interferometry. He is a research scientist at the Research Laboratory of Electronics at the Massachusetts Institute of Technology. He is a member of Sigma Xi, Phi Beta Kappa, the Optical Society of America and the American Physical Society.

**H. John Caulfield** is a former editor of *Optical Engineering* and winner of many SPIE awards (Gabor Award, President's Award, Governor's Award, Fellow, etc.). He has published prolifically in holography, optical processing, signal processing, and metrology. He is currently chief scientist of Northeast Photosciences, Inc., and also research professor of physics at Fisk University.

**Jean-Marc Fournier** is a scientist at the Rowland Institute for Science in Cambridge, Massachusetts, a nonprofit institution founded by Edwin H. Land in 1981. Dr. Fournier has been an invited professor at the Swiss Federal Institute (EPFL) in Lausanne and at Ecole Normale Superieure in Paris. He received his PhD from the University of Besançon, France, in 1970. His areas of concentration include photosensitive materials and diffractive optics. He has also performed research on the optical manipulation of micron size objects, which was then applied to optical trapping and optical binding. Most recently, his interest has been in Lippmann interference photography, and in the interferometric detection of very small time-dependent phase shifts.

**Philip Hemmer** is a physicist at Rome Laboratory, Hanscom Air Force Base. He received a BS in physics from the University of Dayton in 1976 and a PhD from MIT in 1984. His research interests include optical signal processing and memories, compensation of turbulence aberrations, and quantum optics.