than double-entry bookkeeping system has been devised. I have heard estimates ranging from Rathjens's claim of a several-fold factor against deploying Safeguard all the way to several- to many-fold factor in favor of it.

Let's talk. Rathjens's final remarks were dedicated to a very strong plea for discussions on arms control with the USSR as quickly as possible. He recognized that the USSR might well not be serious, but he does observe that there is an apparent hold in their current deployment of ABM components and that the prospects for success will diminish with time as either or both nations proceed with ABM and MIRV programs.

The last speaker of the evening, Brennan, mathematician and staff member of the Hudson Institute, declared his thesis in the title of his talk: "In Defense of Missile Defense." A number of the points that Brennan made echoed those already covered by Wigner, but there were additional observations and remarks that are pertinent to the ABM issue in general and the Safeguard agony in particular. Brennan made the observation that, in fact, a major war can actually happen. Perhaps an uncontrolled development from Mid-East abrasion. In view of the possibility of a thermonuclear conflagration we need some sort of response, and Brennan asserts that even \$15–25 thousand million for defense could cut our industrial and population losses from perhaps 50% in an undefended posture all the way to perhaps 10–20%. This assumes of course that the Soviets do not respond, but, Brennan asserts, even with a partial Soviet response the "offset" will still permit some 60 million lives to be saved in the United States.

Brennan claims that we have not in fact found cheap penetration aids and that we can therefore have some confidence in the technical aspects of our proposed defense.

In the strategic balance Brennan asserts that a defense really does inhibit the probability of war because it introduces absolutely unevaluable uncertainties. This is particularly true for the Soviets, who are extraordinarily defense oriented and have spent three times more on air defense, for example, than we have. Brennan then remarked that the US investment, since the second world war, has been roughly \$55 thousand million on air defense alone, and the system currently costs approximately \$2 thousand million per year to operate.

Avoiding the sword. Brennan's final point was a plea for defense as a possible way out of the "nuclear sword of Damocles" under which we all are living. He asserted, "We have much more interest in live Americans than in dead Russians," a point that could hardly be disputed.

I think that very few people who attended this session changed their minds. I do believe, however, that very few left the session without some exposure to different orchestrations of perhaps already familiar themes. The evident respect of the audience for both the issues and the speakers was a gratifying reaffirmation of the political as well as technical integrity of APS. I was told that one of the reporters from a major metropolitan daily walked out about two thirds of the way through muttering, "This is the damndest nonevent I've been dragged to all year." I think he paid us physicists a very gracious although unintended compliment. Because even though physicists can, and must, participate in a political amphitheater, it is my fervent hope that these actions will continue to derive their integrity and substance from thoughtful reviews, an excellent example of which was this ABM symposium.

BRENNAN

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I am grateful to all of the symposium speakers for careful perusal of this report and their helpful revisions.

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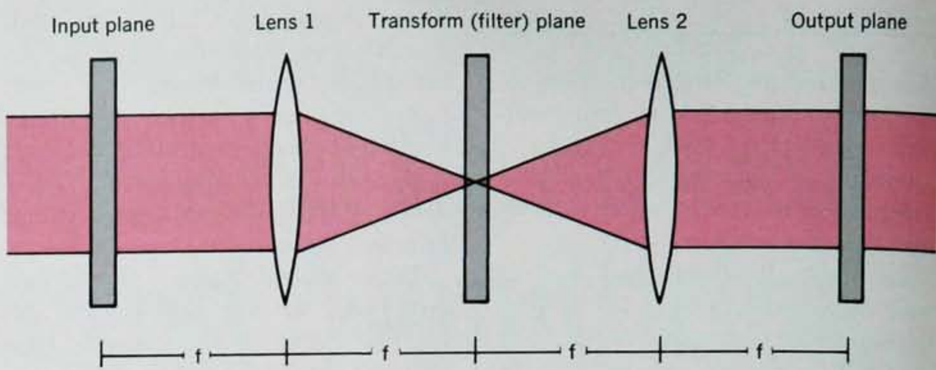
More Applications for Coherent Optics and Holography

Filters that restore clarity to blurred images, phase-contrast image enhancement, imaging with partially coherent light, direct input and output for optical processing in "real time" (without the photographic stages involved in preparing a transparency for input and without light-sensitive emulsion for output)—these were some of the topics covered in a recent symposium on coherent optics.

Held 17–18 April at Oakland University, Rochester, Mich., the meeting was the fourth in a series of conferences held in connection with the dedication of the new Dodge Hall of Engineering. Keeve Siegel, of KMS Industries, Ann Arbor, Mich., was chairman of the symposium, and individual sessions were chaired by Siegel, George Sinclair of the University of Toronto and Samuel Silver of the University of California at Berkeley.

Spatial filtering. One thread that ran through all sessions concerned the theory and applications of coherent optical processing systems. (Some possible applications in the biological field are discussed by Ernest J. Feleppa in his article on page 25 of this issue.)

The basic geometry of the systems we are concerned with is shown in the figure overleaf. The input plane, which normally contains a photographic transparency or perhaps some type of electroöptical transducer, is illuminated from the left by a plane wave of coherent light—usually from a laser. The complex amplitude transmittance of the input plane can be thought of as representing a two-dimensional spatial input signal. The light is diffracted at this input plane, and lens 1 causes the complex amplitude of the light to be distributed in the transform (filter) plane in proportion to the two-dimensional Fourier transform of the input signal. This diffracted light is then recombined by lens 2 (which takes the inverse trans-



SPATIAL FILTERING. Plane coherent light is diffracted at the input plane, and lenses 1 and 2 make the Fourier transform and inverse transform, respectively.

form) to form the image of the input signal in the output plane. If a spatial filter in the form of a mask with a certain complex amplitude transmittance is inserted in the transform plane, the image in the output plane will be altered in some hopefully desired way.

George Stroke, of the State University of New York at Stony Brook, described a number of such filtering experiments in which the purpose was to restore blurred images. These optical processing experiments are most readily analyzed with the mathematics of linear-systems theory. Thus the output image can be written as a convolution of the input signal with an impulse response. If the output image is blurred in some known manner (for example, by motion or defocusing) corresponding to a particular impulse response, the blurring can in principle be removed by inserting the proper complex filter in the transform plane. The proper filter will be the inverse of the Fourier transform of the impulse response, so that it will have the effect of undoing the blurring.

One problem associated with trying to construct such inverse filters is that in every place where the Fourier transform of the impulse response has a zero, the inverse filter will have a pole. Louis Cutrona, of KMS Industries, Inc, indicated that such poles result from the demand that the restored image be zero outside of some region. He showed how these poles could be removed by giving up that requirement, which may not be a handicap because only the region of the restored image is of interest.

Filter construction. A number of techniques for constructing a given complex spatial filter exist. In one technique pure-amplitude and pure-phase filters are made separately, the phase filter being formed by vacuum deposition of thin films. Complex filters can also be made by recording, holographically, the Fourier transform of the desired impulse response. Adolph Lohmann, of the University of California at San Diego, described how complex filters can be synthesized with the technique for making binary, computer-generated holograms. In this case the filter consists of many transparent dots on an opaque background, and thus the amplitude transmittance of the filter is real and non-negative. Nevertheless the phase of the light is affected by the relative position of the dots, which make up a type of diffraction grating. A rectangular grid divides the filter into a large number of tiny cells. The width of a small rectangular dot within each cell controls the magnitude of the complex amplitude transmittance of the filter at that point, and the position of the dot within the cell controls the phase. Lohmann showed examples of how such filters had been used for phase-contrast enhancement, Schlieren filtering and one- and two-dimensional differentiation.

Real-time devices. With the basic optical-processing geometry shown in the figure one has typically used photographic transparencies as the input signal and the spatial filter and has often recorded the output signal on photographic films as well. Photographic emulsions used as integral parts of the processing system are cumbersome and time-consuming, and many attempts have been made to replace the photographic film with real-time input, output and filtering devices. Marvin King, of the Riverside Research Institute, described a number of experiments in which an ultrasonic light modulator is used in the input plane to convert electrical signals to a complex amplitude transmittance function. The electrical signal drives a piezoelectric crystal, which sets up an acoustic wave in some type of transparent medium. The resulting variations in refractive index throughout the medium will represent a complex signal in the input plane, with a Fourier transform that will be represented by the resulting diffracted light in the transform plane. An array of such ultrasonic transducers can be placed adjacent to each other to form a multichannel input signal. These types of real-time input devices have been used for spectrum analysis, correlation and pulse-compression experiments, array-antenna processing, and signal recorders and processors.

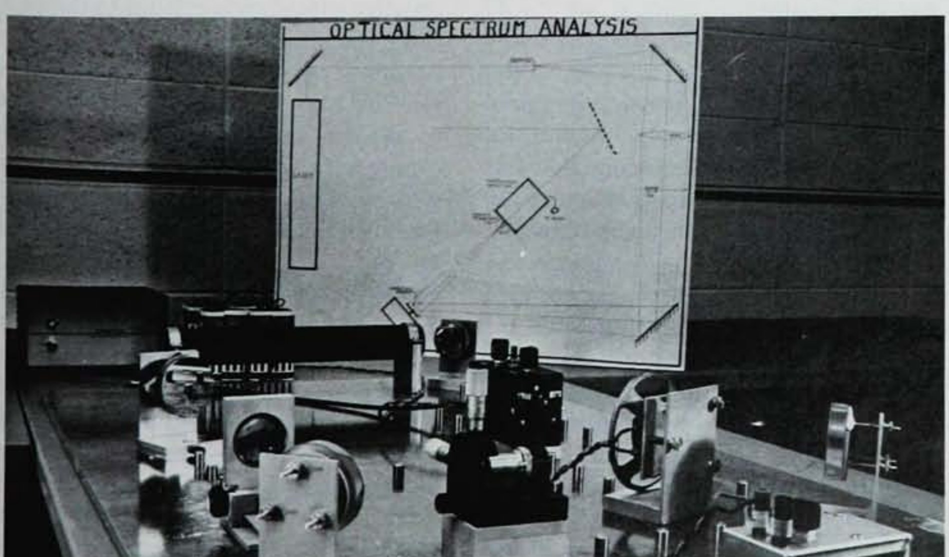
Real-time electroöptical devices can also be employed in the transform (filter) plane. Euval Barrekette presented results of some experiments, done at the IBM Thomas J. Watson Research Center, in which the light reflected from various parts of the filter plane was controlled electrically. This was done by controlling the amount of charge on an electroöptic crystal with an electron beam, which in turn varied the electric field and therefore the amount of birefringence at different locations on the crystal.

Richard Haskell, of Oakland University, described experiments (see photo below) that engineering students perform in conjunction with their study of Fourier analysis. In one of the experiments, one-dimensional spatial signals recorded on photographic film are inserted in the input plane. A vibrating mirror causes the light distribution in the transform plane to be repeatedly swept past a photodiode detector, which then displays the power spectrum of the input signal directly on an oscilloscope. Results of a second experiment were also presented in which the convolution or correlation of two spatial signals are recorded directly on an oscilloscope.

An off-axis point source in the input plane will cause the transform plane to be illuminated with a tilted plane wave. In his talk on computer-generated holograms, Lohmann described how a binary hologram could then be inserted in the transform plane to produce a predetermined image in the output plane. As the output plane and the transform plane are related by a Fourier-transform operation, the digital computer finds the Fourier transform of the desired image and thus determines the required amplitude and phase at each point in the transform plane. This in turn will determine the size and position of the dot within each cell of the hologram in a manner similar to that described above for synthesizing complex spatial filters.

All of the work described thus far has been based in one way or another on the Fourier-transforming property of lenses. This property was recognized as long ago as 1873 by Ernst Abbe, who used these ideas in his description of image formation in a microscope. The circumstances surrounding Abbe's work and a number of historical sidelights were discussed by Lohmann in his talk.

The problems of imaging with coherent and partially coherent light and the properties of holographic detection schemes were considered by a number of speakers. Emmett Leith, of the University of Michigan, discussed the



UNDERGRADUATE EXPERIMENT performs real-time optical spectrum analysis.

problems associated with coherent illumination. To overcome the bothersome diffraction effects that are inherent with coherent light some type of diffuser is often used. However, this diffuser gives rise to a speckle noise effect, arising from the destructive and constructive interference of the light from the many scattering centers of the diffuser. Leith described a technique for alleviating the speckle noise that makes use of a properly designed phase type of crossed diffraction grating.

Arwind Marathay, of Technical Operations, Inc, talked on the general problem of imaging with partially coherent light. The basic quantity of interest is the mutual coherence function, which is the cross-correlation of the optical field at two different points in a plane normal to the optical axis. For quasi-monochromatic light the time delay associated with the mutual coherence function can be set equal to zero, and the resulting function, called the "mutual intensity," characterizes the light at a given plane in the optical system. The mutual intensity in the image plane can be found from the mutual intensity in the object plane by a superposition integral. Thus the imaging system is linear in mutual intensity. In the limit of coherent illumination the optical system is linear in complex amplitude and is characterized by an impulse response whose Fourier transform is the coherent transfer function. In the limit of incoherent illumination the optical system is linear in intensity and is characterized by a different impulse response whose Fourier transform is the optical transfer function.

This optical transfer function associated with incoherent imaging is related to the coherent transfer function by an autocorrelation operation. In his talk Marathay pointed out that for objects transilluminated with partially coherent light the relationship between the object intensity and the image intensity is nonlinear. He described how an apparent transfer function could be defined in terms of the particular type of object used. Cutrona expressed his view that a transfer function describing an optical system should ideally be only a function of the system and should not depend on the type of object or the type of light that is used. For this reason he felt that the coherent transfer function, which is related in a simple way to the (possibly complex) pupil function, is the best way to describe an optical system. The behavior of the system under incoherent or partially coherent illumination can then be calculated once the coherent transfer function is known.

Interferometric imaging. Joseph Goodman, of Stanford University, described some analogies between holography and what he termed "interferometric imaging." In this analogy the complex degree of coherence, as given by the Van Cittert–Zernike theorem, plays a role analogous to the complex amplitude function in ordinary holography. A reference beam can be used to encode the phase information of the complex degree of coherence. Goodman extended the analogy to show how such interferometric imaging can form aberration-free images through aberrating media and even how, in principle, three-dimensional interferometric images can be formed. He gave an example of how this technique might be implemented with a lens as the interferometric device and pointed out the relation of such a device to Lohmann's incoherent hologram.

The use of holograms to encode phase information also plays a role in the solution to an inverse-scattering problem described by Emil Wolf of the University of Rochester. He presented a theoretical solution for the problem of determining the three-dimensional variations in the complex refractive index of weakly scattering objects. The scattered waves can be represented in terms of an angular spectrum of plane waves where each scattered wave carries information about one of the Fourier components of the three-dimensional object. This angular spectrum is related to the two-dimensional Fourier transform of the scattered field in a given plane, which may be calculated from measurements of the transmission function of holograms. In general many holograms will be needed, corresponding to different directions of illumination of the object.

Analogies between coherent light and microwaves have led to numerous attempts to apply microwave ideas in the optical region. Dean Anderson, of North American Rockwell, described some nonlinear experiments involving the parametric interaction of optical waves. In these experiments the light is guided by thin films acting as dielectric waveguides. Small glass fibers can also serve as optical waveguides, and Narinder Kapany, of Optics Technology, Inc, presented experimental results that showed such fiber waveguides supporting a large number of different modes. He also illustrated the coupling that can occur between adjacent fibers by showing the results of some interesting experiments in which the optical energy oscillates between two fibers.

Radar. Another thread that ran through the conference was the close relationship between coherent optics and various aspects of radar theory and applications. Gary Cochran, of KMS Industries, Inc, reviewed the history of synthetic-aperture radar, indicating how the modern development of holography relating to the off-axis reference beam had its origin in work at the University of Michigan in synthetic-aperture radar. He noted that the cycle had become complete; the latest processing systems for synthetic-aperture radar data use holographic techniques for recording the final image. Other analogies and relationships between coherent optics and radar were discussed by Emmett Leith in connection with the simulation of the azimuth ambiguity and by Marvin King in connection with the optical processing of pulse-burst radar. Paul Wild, of the Division of Radio Physics, CSIRO, in Sydney, described the image-forming radio telescope that has been built in Australia to make rapid measurements of the radio emission from the sun. The antenna array consists of 96 parabolas, each having a diameter of 45 feet (14 meters), arranged on a circle whose diameter is about 3 kilometers. The signal from each parabola is fed to a computer that processes the data and displays an image of the solar activity on a cathode-ray tube. Future possibilities include a direct coherent optical simulation processor, in which the signals from the parabolic dishes drive an array of ultrasonic transducers in such a way as to produce a direct image from the received radiation.

Many opinions can be heard on the possible future role of coherent optics. One often hears that holography is "a solution looking for a problem." However, Keeve Siegel for one insisted that those who are ready to abandon coherent optics and holography at this time would be making a serious mistake. Only time will tell.

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