COHERENT OPTICAL ENGINEERING

Edited by

F. T. ARECCHI

and

V. DEGIORGIO

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A selection of lectures

given at the International School of Quantum Electronics,
Versilia, Tuscany, Italy,
1–15 September 1976

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1977

NORTH-HOLLAND PUBLISHING COMPANY
AMSTERDAM • NEW YORK • OXFORD

North-Holland ISBN: 0 444 85080 5

PUBLISHERS:
NORTH-HOLLAND PUBLISHING COMPANY
AMSTERDAM•NEW YORK•OXFORD

SOLE DISTRIBUTORS FOR THE U.S.A. AND CANADA:
ELSEVIER / NORTH HOLLAND, INC.
52 VANDERBILT AVENUE, NEW YORK, N.Y. 10017

Library of Congress Cataloging in Publication Data

Nato Advanced Study Institute on Coherent Optical Engineering, Lucca, 1976.
Coherent optical engineering.

1. Optics--Congresses. I. Arecchi, F. T. II. Degiorgio, V. III. Title.
TA1505.N37 1976 621.36 77-15129
ISBN 0-444-85080-5

PRINTED IN THE NETHERLANDS

PREFACE

This volume contains the invited lectures and seminars presented at the NATO Advanced Study institute on Coherent Optical Engineering, sixth Course of the International School of Quantum Electronics, affiliated with the Centre for Scientific Culture E. Majorana, Erice, Sicily. The Institute was held at Villa Le Pianore (Lucca), Versilia, Italy, September 1-15, 1976.

The aim of the Institute was to provide a presentation of several optical measurement methods, including holographic and speckle interferometry, laser interferometry, laser telemetry, intensity correlation spectroscopy and Doppler velocimetry, white light and "moiré" techniques, and to describe the state of the art in the field of optical information processing. The Course was made self-contained by a series of lectures which gave the basic principles underlying Coherent Optical Engineering and reviewed the most important optical devices, such as laser sources, laser deflectors and modulators, detectors and recording media.

The members of the Organizing Committee were:

- F. T. Arecchi } Directors of the International School of Q. E.
- D. Roess } Directors of the International School of Q. E.
- J. M. Burch, National Physical Lab., Teddington, U. K.
- V. Degiorgio, CNR and CISE, Milano, Italy
- A. W. Lohmann, University of Erlangen, Erlangen, Germany
- S. Lowenthal, Institut d'Optique, Orsay, France

In addition to those published here, the following lectures and seminars were also given at the Institute:

M. Bertolaccini : "Photoelectric Detectors"
J. M. Burch : "Holographic Interferometry-White Light and Moiré techniques - Laser Resonators"
R. Leighty : "Optical Processing in Photogrammetry"
W. Lukosz : "Fourier Optics"
V. Russo-Checcacci : "Optical Processing"
G. Toraldo di Francia : "Information Content of an Optical Image"

We wish to express our appreciation to the NATO Scientific Affairs Division whose financial support made this Institute possible. We also acknowledge the contribution of cultural institutions and industries as :

CISE
CNR (Italian National Research Council)
Deutsche Physikalische Gesellschaft
European Research Office
IBM Italia
PHILIPS Eindhoven
SIEMENS München

We finally thank Dr. V. Fossati-Bellani and the secretaries of the Divisione Elettronica Quantistica, CISE, Mrs. G. Ravini and Miss M. Oriani, for their precious assistance in the organization of the Institute and in the preparation of these proceedings, and Miss A. Camnasio of Servizio Documentazione, CISE, for her assistance during the School days.

F.T. Arecchi
V. Degiorgio

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AN INTRODUCTION TO HOLOGRAPHY

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With the award of the 1971 Nobel Prize in physics to Dennis Gabor, holography reached a new pinnacle of prestige. Gabor's method, simple and elegant, solved in quite a general way the basic problem of recording the phase, as well as the amplitude, of a wave. In three principal papers between 1948 and 1951 [1], he developed the theory in considerable depth and offered convincing experimental results. Gabor's original purpose, to record electron waves and regenerate them at optical wavelengths, thereby compensating with optical techniques for the uncorrectable aberrations of electron lenses, is an historical point that today is of secondary importance. However, the holographic process has been revealed to have far more potential than one could, at that time, have imagined.

Interest in holography continued strong for several years afterward, and produced some notable pioneers, such as G.L. Rogers, M.E. Haine, J. Dyson, T. Mulvey, A.W. Lohmann, and others. Despite the initial impetus, however, interest in holography waned in the middle 1950's, although activity never completely ceased.

The principal reason for the loss of interest was the relatively poor imagery, due mainly to the well-known twin image, which occurs because the recording process is sensitive only to the intensity of the incident radiation. As a consequence, the reconstruction process not only recreates the original wave, it also creates a conjugate wave that, under collimated illumination, forms an image in mirror symmetry to the "true" image with respect to the plane of the hologram. Whichever image one elects to use, he must view if against the out-of-focus background of the other, and the result is a noisy image.

MODERN HOLOGRAPHY

In the early 1960's, several papers appeared that proved to be forerunners of the great explosion of activity that ushered in the next stage of holography. Juris Upatnieks and I announced at the October 1961 Optical Society of America meeting a number of new concepts, including the off-axis or spatial-carrier frequency method of holography, which removed the twin-image problem in a simple and practical way [2]. In this method, the reference and object waves are brought together at an angle, to form a rather fine fringe pattern. The resulting hologram, behaving like a diffraction grating, produces several non-overlapping diffracted orders. The zero-order wave produces the usual inseparable twin images which, in combination with other defects of in-line holography, result in poor imagery; but each first-order diffracted wave produces an image of high quality.

When, however, we extended the process to continuous-tone object transparencies instead of the black and white transparencies used in holography until then, another defect became prominent. The difficulty was the well known "artifact" problem of coherent light-each extraneous scatterer (for example, a dust particle) produces a wake of diffraction patterns that contaminate the resultant image. We surmounted this problem with diffused coherent illumination, which properly used, smooths the field produced by these scatterers.

The diffused-illumination hologram is different in appearance from ones made with undiffused illumination. The latter show the characteristic diffraction patterns of the original objects. These diffraction patterns bear a definite, although not always obvious, relation to the object. Also, broad, relatively low-spatial-frequency regions tend to retain their identity, since the defocusing process is most pronounced on high spatial-frequency components.

Holograms made with diffused illumination show no discernible diffraction patterns from the object. Rather, the diffused light, when scattered by the object, acquires the same uniform, grainlike structure that it had when emitted from the diffuser. This pattern is homogeneous and always has the same general appearance, regardless of the object, except for very simple object composed of a few discrete points.

Holograms made with diffused illumination have the property that each point, or each element, regardless of its size, scatters to all points of the hologram. Consequently, information about each portion of the object is recorded over the entire hologram, and each portion of the hologram, no matter how small, reproduces the entire object to within the limitations imposed by the size of the portion, which becomes the limiting aperture of the process.

The most significant property of the diffused-illumination hologram is that the images it produces can be seen without the need for an eyepiece. The virtual image can be seen by looking "through" the hologram as if it were a window, and the real image can be seen suspended in front of the hologram. If the diffuser had not been used in making the hologram, the reconstruction could not be thus observed. To explain why this is so, let us consider what happens when one observes a transparency illuminated from behind with a point source. Except for some scattering, the observer receives light only from the part of the transparency that lies on the line between the point source and the pupil of the eye; this part is usually negligible, However, if a diffuser is placed between the source and the transparency, light from all points of the transparency reaches the eye, and the whole transparency is seen.

This argument readily applies to the hologram case if one thinks of the hologram as reconstructing not only the transparency, but also the diffusing plate. Thus, the observer sees the reconstructed image as if it were illuminated by a diffuse source.

Finally, we went to the use of arbitrary, three-dimensional reflecting objects. The resulting are, optically speaking, a highly exact replication of the original object, fully three-dimensional and with full parallax.

Stability and Coherence Requirements

As the holograms became more sophisticated, the requirements on their construction became more severe. As is well known, holography today is generally carried out on a granite bench, and the techniques of interferometry are brought to bear; for example, optical elements are either massive or securely held so as not to vibrate. Yet, the early Gabor type holograms can be produced on an ordinary optical bench mounted on a very ordinary table. Where along the line have these great stability requirements arisen? In general, they have increased for each of the various steps we have enumerated.

Of course, some stability is required even for ordinary photography; if the camera moves too much, the image is blurred. It is easily shown that, for Gabor, or in-line holograms, the stability requirements are just those of conventional photography. As we go to the off-axis method, the stability requirements increase somewhat. The fringes are finer, and it takes less movement of, for example, the recording plate, to blur them out on the hologram. Going to diffuse illumination produces a still greater stability requirement, since in general, with diffused illumination, the hologram structure becomes much finer.

The really great jump, however, occurs when go to reflecting objects, and it is very easy to see why. If the object transparency moves during recording, the optical path of the transmitted light changes little, and the fringe pattern to be recorded also moves only slightly. But when light is reflected from the object, an object movement of a half wavelength of the illuminating light results in a phase change of the object beam of about 2π, and the fringe shift is a full cycle. The stability requirements have now become so severe that the holography experiment is driven to the granite bench. All of the previously noted forms of holography can be done perfectly well on an ordinary table, but reflecting elements in the system put an end to this simple state of affairs.

A similar evolution has occured with the coherence requirements. The holograms of Gabor were made with the Hg arc source, but of course such a source is not at all satisfactory for the holography of 3-D, reflecting objects.

Proceeding as before, we start with the coherence requirements for ordinary photography. Of course, there are none. From photography to Gabor's holography, there is a jump, since this form of holography has definite, although modest, coherence requirements. If the resolution elements on the object are of linear dimension d, and if each such element produces a diffraction pattern of linear dimension L on the hologram, then the coherence requirement is

$$\Delta\lambda \doteq 4d/L$$

The quantity L/d we may call the expansion ratio. It is interesting that the coherence requirement is given by this single parameter. Calculations show the coherence requirements to be quite modest; for example, for an expansion ration of 100 (which represents an increase of spread function area by a factor 10^4 between object and hologram) and for λ = 5000 Angstroms, the source spectral width $\Delta \lambda$ can be as great as 200 Angstroms. The 5461 line of the Hg arc can be many times narrower than this.

When we proceed to off-axis holography, the fringes are finer, and there are more of them. Therefore, one might expect the coherence requirements to be greater. This is not necessarily true; the off-axis hologram can be thought of as containing the diffraction information on a spatial carrier, and it can be shown that the operation of placing a signal on a spatial carrier does not require monochromaticity. There should be ways of doing off-axis holography with the same coherence requirements as for in-line holography, and this is indeed the case. In particular, the use of a diffraction grating as a beam splitter leads to systems of off-axis holography with coherence requirements no more than that of the in-line systems.

For diffused illumination, the espansion ratios are greater, and therefore the coherence requirements are also greater. Finally, for 3-D reflecting objects, the coherence requirements take a tremendous jump; rays reflected from all parts of the object must interfere with the reference beam; thus, the object depth should be about twice the source coherence length. For an object of 10 cm depth, the coherence requirement is about 20 cm. This new requirement is so great that it makes the previous requirement small by comparison. In general, only the laser can effectively meet this requirement, and so it is only for the 3-D, reflecting object that a laser is required. All of the previously-noted types of holography can be done quite well with the Hg source, and indeed, our first successes in off-axis holography had been achieved with the Hg source.

Since hologram viewing involves essentially a retracing of the ray paths involved in making the hologram, we expect that these same arguments apply in viewing holograms. In general, this expectation is correct, but with several exceptions, the principal one being that holograms of 3-D, reflecting objects require no more coherence for viewing than holograms of transparencies; the reason is that the large optical path differences arising through reflection from 3-D objects do not occur in the viewing process, since this process does not involve any such reflections.

VOLUME HOLOGRAMS

In 1962, Yu.N. Denisyuk of the USSR introduced a new concept into holography, the "volume hologram", which combines holography with the Lippman color process [3]. Object and reference beams are introduced from opposite sides of the recording plate, and the resulting fringes are embedded within the emulsion as surfaces running nearly parallel to the emulsion surface, with half a wavelength spacing between them. Typically, the number of fringes in a cross section is about 50, although for very thick (a few mm) recording materials, there may be thousands. The twin image is eliminated by the thickness effect and, in addition, the holograms, because of their wavelength selectivity, can be viewed in white light derived from a point source. Denisyuk's work is a cornerstone of modern holography.

One could certainly combine our technique, involving separately-produced object and reference beams, with the Denisyuk technique. Suprisingly, this combination was first made only in the latter part of 1965, and almost simultaneously by three groups. Our group reported and demonstrated such holograms at the Spring 1966 meeting of the Optical Society of America, as did also G. Stroke and A. Labeyrie. However, N. Hartman of the Battelle Institute had been the first to do this and consequently was awarded the patent.

THE GREAT SURGE

By late 1964, holography had become probably the most active field of research in optics, engaging hundreds of groups throughout the world.* Discovery and invention dominated the next three years; this period produced several techniques of color holography, hologram interferometry in its various forms, techniques for holographic imagery through scattering and aberrating media, and many other basic concepts. The vast potential that had been inherent in holography now emerged with astonishing force.

Holography was found capable of an astonishingly wide variety of tasks that were normally done in other ways. Holographic methods could be useful in optical metrology and offered some interesting possibilities for spectroscopy. Optical memories using holographic techniques seemed destined to make significant inroads into the huge computer-memory field. Optical reading and feature-recognition machines that used holography were visualized. Microscopy, at least in the visible wavelength range, seemed promising. With hologram interferometry, a wide variety of non-destructive testing techniques became available, ranging from early detection of fatigue failure, to the detection of "debands" in multilayered materials such as tires and honeycomb panels, to the determination of heat flow in transparent materials, to the study of bending moments and to the dynamic operation of audio speakers and other sound-transducing equipment. A most ingenious and unlikely application of hologram interferometry is the determination of the complex mode structure of a laser [4]. Merely to list the applications of hologram interferometry in reasonable completeness would fill a page. Even in conventional interferometry, it was found that one could apply to the hologram essentially all the techniques such as schlieren, dark field, and phase contrast-normally done with the actual object [5].

Holography can be used to detect and examine aerosol particles, such as atmospheric pollutants. Not only was holography unique for visual displays of many kinds, including portraiture, but it could also be used in instrumentation for conventional stereo imagery. Holographically produced optical elements showed promise for improving the performance of optical elements. The versatility of holography seemed limitless.

Some of these applications appear promising now, others not so. If only a few proved viable, holography will have a bright future.

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AN INTRODUCTION TO QUANTUM OPTICS

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1 – Quantum Optics : a heuristic approach – Terminology and Numerology

1.1 Definition of Quantum Optics

The term "quantum electronics" was first used in 1959 at a conference dealing with the physical and engineering uses of the MASER (Microwave Amplifier by Stimulated Emission of Radiation) and MASER oscillators in high resolution spectroscopy and in the handling of electromagnetic signals at $\lambda \sim 1$ cm.

Half a year later, the first LASER was operated (L stays for light. The L has replaced the M because this time the generated radiation is at $\lambda \lesssim 1\ \mu$m).

Since 1960 the LASER has become a useful device in many areas of physics and technology.

In the spectral range of interest, it is more convenient to speak of Quantum Optics, rather than Quantum Electronics.

Quantum Optics can be approached from three points of view, namely:

i) physics of the stimulated emission processes;

ii) coherence and cooperative phenomena in radiation-matter interaction;

iii) application of the LASER related to its spectral purity.

We shall discuss the three aspects in sequence, defining the terms and giving the orders of magnitude.

1.2 Physics of the stimulated emission processes

If the e.m. cavity where we are considering the radiation-atom interaction is a rectangular cavity of sides X, Y, Z; volume V = X Y Z, then the solution of the wave equation, with periodic boundary conditions, yields the plane wave expansion for the field

$$E(x,y,z,t) = \sum E_{k}(t)\, e^{i(k_1 x + k_2 y + k_3 z)} \qquad (1.1)$$

where $k_1 = n_1 \cdot 2\pi / X$
$k_2 = n_2 \cdot 2\pi / Y \qquad (n_i = 1, 2, \ldots)$
$k_3 = n_3 \cdot 2\pi / Z$

For each set of $k_{1,2,3}$ we have a different field configuration, or mode.

The dispersion relation imposes a constraint between frequency ω and amplitude $k = \sqrt{k_1^2 + k_2^2 + k_3^2}$ of the k vector

$$\omega = c\,k \qquad (1.2)$$

In k space (Fig. 1.1) each mode occupies an elementary volume

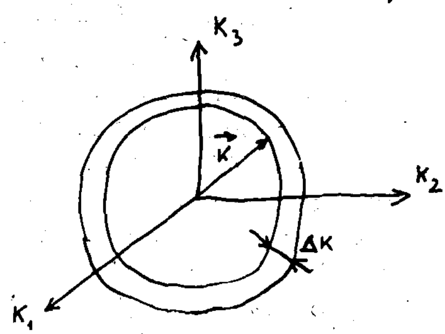

Fig. 1.1

$$\delta^3 k = \delta k_1 \, \delta k_2 \, \delta k_3 = \frac{(2\pi)^3}{V}. \qquad (1.3)$$

In a spherical shell of radius k and thickness Δk there are

$$M = 2 \, \frac{4\pi k^2 \Delta k}{\delta^3 k} = \frac{k^2 \Delta k}{\pi^2} V \qquad (1.4)$$

modes. The extra-factor 2 accounts for the two possible polarizations for each k vector. Hence the mode density in frequency is

$$dM / d\omega = \omega^2 \, V / \pi^2 , \quad \text{or}$$

$$\frac{dM}{d\nu} = \frac{8\pi \nu^2}{c^3} V \qquad (1.5)$$

If the cavity contains radiators (atoms on the walls or inside) in thermal equilibrium at a temperature T, then the electromagnetic energy density in the cavity is given by Planck's blackbo-