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COMPUTER OPTICS: ACHIEVEMENTS AND PROBLEMS

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Abstract—The concept of computer optics (CO) is clarified and the prerequisites of its advent are described, along with stages of its development. Basic CO activities are identified such as design, development and investigation of CO elements. Each of these areas is briefly analysed. Branches of CO are discussed which relate to electromagnetic and acoustic waves in the X-ray, ultraviolet, visible, infrared, submillimetre and millimetre wavebands. Consideration is given to CO elements such as zone plates, kinoforms, focusers, analysers and mode composition synthesizers, Bessel optics elements, programmable lattices, etc. Future CO developments are discussed.

WHAT IS COMPUTER OPTICS?

It is widely known that computers have penetrated into various fields of human activity. The term "computer science" is well established. In a broad sense of the term "computer optics" is both computers in optics and optics in computers. It encompasses the numerical solution of diffraction problems, computer-aided design (CAD), automatic production of optical systems, image processing, numerical optical experiments, optical processors and memory devices, and digital holography. However, in this survey the authors would like to concentrate on the essentially new application of computers to the design of a whole class of optical elements with previously unattainable performance specifications.

Computer optics, then, is about the computer-aided production of optical elements capable of performing specific transformations of wave fields. It extends the available set of construction elements in optical systems. In addition to the traditional lens, prism and mirror, optical elements possessing a broader range of functions have made their appearance. Among the new series of computer optics elements, the kinoform is typical [1]. As an example of their use, kinoform correctors combined with ordinary lenses can be employed in designing optical systems with reduced spherical aberrations [2]. Although other applications exist [3], we do not want to imply that the design of kinoforms is the main challenge of computer optics.

The application of computer optics elements opens up completely new vistas, especially in coherent optics. An important feature of these elements is their flatness, and consequently their small overall size, compared to regular optical elements.

The newly-coined term "computer optics" needs to be defined. Over the years the present authors have used the term "flat optics" to refer to computer-aided design of optical elements, and this term became quite accepted. Nevertheless, it does not do full justice to the computer's role, as it emphasizes the size feature at the expense of other characteristics. Furthermore, the recent ideas of extending phase relief plots from flat to spherical or even more complicated shapes certainly renders the term "flat optics" inappropriate.

The basic strategy in computer-aided design of optical elements is the following. In general, the optical element utilized in transmission or reflection of radiation is characterized by an amplitude or phase function, respectively. These characteristic functions must be determined by solving the appropriate wave field transformation problem. In the simplest cases analytic expressions are available, for example in specifying the phase function of spherical or cylindrical lenses. But in general the optical element characteristics can only be determined by computers. In this role the computer may be used in numerical calculations, as well as in solving inverse problems. Thus, in the design of optical elements involving a set of orthogonal basis functions, one requires calculation of the superposition of such a set with a reference plane wave, in essence the construction of a mathematical hologram, whose solution on the computer is an example of a direct problem. On the other hand, in designing radiation focusers their phase functions are determined by the numerical solution of an inverse problem. These are examples of how the computer is utilized at the design stage to determine optical element characteristics. Having stored these in the memory, the next

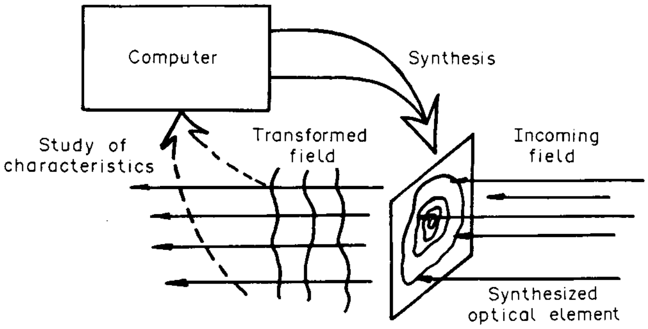

Fig. 1. Computer optics—the computer assisted production of optical elements capable of carrying out specified wave field transformations.

problem is their realization on the physical system by software, interfacing the computer with the production line. At this stage the computer fulfils the role of automatic control. Even if the computer is not absolutely necessary in controlling diffraction grating ruling machines, where the cutting tool path is simple, digital control is essential for the complex ring-width control algorithm involved in zone plate production. The process of thin lens manufacture is even more complex: both the annular radii and the phase profile must be programmed. Manual production of such elements is practically impossible.

The computer therefore serves as a control device in automated production of the optical element. After production the element is tested and approved. Its performance data are normally recorded in terms of various kinds of light intensity distributions: shadow pattern, interferogram or hologram. Once again the computer enters, to process, image and interpret the experimental data, as visual observation and hand processing are totally inadequate in providing quantitative results. A further point is the key role of the computer in performing numerical experiments or simulations to provide insight into computer optics. The production of computer optics elements is a complex iterative process in which the computer is in constant interaction with designers, and technical and research personnel. The term "computer optics" recently coined by the authors is indeed justified by the gamut of computer functions we have enumerated. Figure 1 illustrates both the production process of elements, as well as the problems dealt with in computer optics.

Work on digital holography served as an important stimulus in the development of computer optics into a scientific discipline in its own right, using quantum electronics, computational mathematics and information theory. Digital holography deals with the production of holograms and the reconstruction of physical holographic imaging by means of computers fitted with input/output devices and specialized mathematical capabilities. The last two decades have seen the publication of over 600 papers on digital holography [4]. A considerable proportion of these is devoted to the computer-assisted production of various radiation spatial filters, rather than actual production or analysis of holograms. In particular, Kozma and Kelly [5] have proposed machine production of spatial filters for use in optically matched filtering of radar signals.

Unfortunately, it must be acknowledged that digital holography's main aim, namely, three-dimensional display, has not yet been realized, and will not be achieved in the near future. Nevertheless, the efforts expended towards that goal have meanwhile yielded interesting scientific results, in the first place in developing new methods of transcribing amplitude-phase distributions onto physical media.

The production by Lesem *et al.* [1] of the kinoform over 15 years ago has had a seminal influence on other workers, the present authors among them, in that the optical elements they produced were all related to the kinoform family. But by the early eighties, as new types of optical elements came into being, it became clear that they were in fact different from earlier types, whether they be kinoforms, Loman–Lee or other holograms, zone plates or Fresnel lenses, though they closely resembled them outwardly. For all these reasons, with the ever-widening role of computers in optics, the time had come to use the terms "computer optics" and "computer optics elements" [6, 7].

We may therefore distinguish the following trends in present day computer optics:

(1) Solution of inverse problems in diffraction theory applied to optical element design;

(2) Development of new technologies for transferring computer-designed elements serving various radiation bandwidths to physical media;
(3) Studies of optical element defects and aberrations;
(4) Computer-aided design and experimental study of computer optical elements;
(5) Construction of radiation focusers;
(6) Design of optical elements to generate and analyse transverse-mode radiation structure;
(7) Construction of wavefront correctors;
(8) Design of spatial filters for optical information-processing systems and digital-optical processors;
(9) Design of kinoform lenses and "aberration-free" objectives;
(10) Utilizing computer optics elements in tackling the problems of laser, medical instrumentation and communication technology, and so forth.

We shall now give a brief discussion of each of these procedures.

1. Solution of inverse problems of diffraction theory in computer optics

Given the phase function of an optical element, one can in principle solve the diffraction problem and obtain the field distribution in the region of interest. Serious computational difficulties may arise in such a programme, primarily due to the magnitude of the task. We shall deal with the direct problem later and proceed to discuss the so-called inverse problem. To clarify the essential physics consider Fig. 2. A flat optical element Φ, situated in a region G of the plane $\vec{u} = (u, v)$, is illuminated by a beam E of monochromatic radiation of wavelength λ. A specified wave field $I(\vec{x}, z)$ is to be formed in region D of the plane $\vec{x} = (x, y)$. The optical element phase function completely determines the beam behaviour in $\vec{u}$, and in particular, in the region of interest $\vec{x}$. The problem then is to provide the phase function $\varphi(u, v)$ which generates the wave field $I(\vec{x}, z)$ of the element. From a mathematical point of view the problem is ill-posed: firstly, the solution may not exist; secondly, it may not be single-valued; and thirdly, it may not be stable. Examples of all three of these will be considered in radiation focuser design. These difficulties are normally associated with certain fundamental limitations imposed in the focusing region by physical laws.

For example, it is well known that the spot diameter D in the focal region can never be less than the diffraction limit dictated by the transverse dimension d of the focusing lens, the wavelength λ and the focal length f, namely that $D \geqslant \lambda f/d$. A similar restriction is imposed on the minimum attainable linewidths on focusing a segment in a plane perpendicular to the propagation axis. The focuser in this case is itself a combination of plane, cylindrical and spherical lenses, all in one optical element. By modifying the form and profile of the focuser's peripheral zone one can redistribute the radiation intensity over the segment, in particular, a uniform distribution may be obtained. The minimum linewidth is controlled by the combination $\lambda f/d$, d being the focuser transverse dimension.

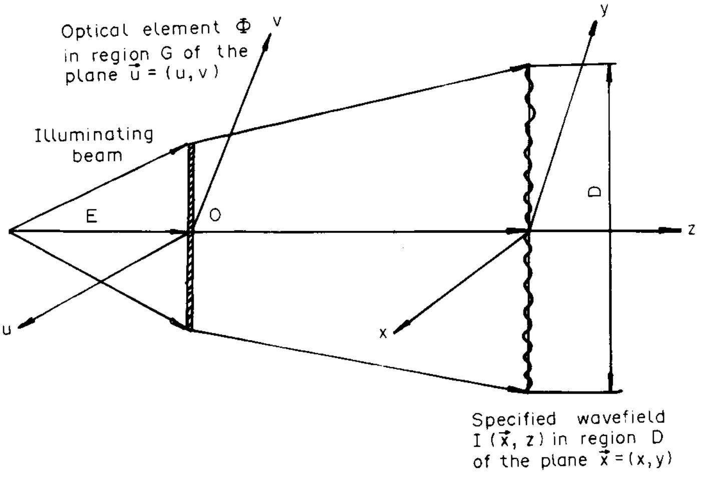

Fig. 2. Formulation of the problem of generating an optical field.

Nor need the lack of solution of the focusing problem be occasioned by contradicting some physical law. If, for example, the focusing region is a three-dimensional spatial curve rather than a plane perpendicular to the optic axis, when definite limitations are imposed by the light energy having to propagate along the optical axis, in accord with the principle of rectilinear light propagation. In particular, when focusing by a narrow cylinder lying along the optic axis, one cannot at the same time demand that all the energy be concentrated in it, and that the intensity outside the narrow cylinder vanish. Clearly, as the cylinder moves away from the focuser, the energy shifts to the peripheral sections nearest to the focuser.

It often happens in computer optics that the solution for the phase function of the focuser is not unique and that many different solutions may result in the same focal region. The point is that there is an inherent uncertainty in forming the required focusing region by the focuser. Let us consider a segmented focuser.

It is well known that any arbitrary segment of a lens fulfils the same function as the whole lens. In particular, therefore, a focuser segment bounded by a rectangle will focus into segments. The diffraction-limited minimal linewidth is thereby increased. A segment bounded by a triangle will likewise focus into segments. Recording four segments on a single such focuser, one may obtain a square or a cross-shaped focuser. We may conceive of this as two different focusers, one of which has four rectangles, and the other four triangular segments, while both allow one to focus radiation into a cross. In this case, the ambiguity in the solution of the inverse problem for the focusing which allows the production of various focusers all performing the same function, is actually a positive advantage, in that one need not adhere to a single unsatisfactory solution.

The ambiguity in focuser synthesis may also be traced to the peculiarity of the phase function employed to describe them, which as we have seen, is spread over the interval 0–2π. Now look at the kinoform production process, illustrated in Fig. 3. Slicing the lens into layers of width $\lambda/(n-1)$ from top to bottom (n is the lens refractive index) one obtains a system of zones. But the same procedure may be carried out in reverse, from bottom to top, resulting in a totally different zone system. In this case the non-uniqueness of the focuser's phase characteristics is not a negative attribute.

Let us now consider the third difficulty with the inverse focusing problem, namely, the instability of the solution. A small change in the focusing region's form and its intensity distribution may give rise to a significant change in the optical element's phase function. Consider the focusing problem in two parallel segments. No matter how small their separation, two segments with phase jumps across their boundary must have been made on the focuser. As soon as the two segments completely overlap the focuser phase function becomes continuous without any break. Focuser amplitude masks with discontinuous phase function and the resulting focusing were reported in [8, 9] where, in spite of breaks, successful focusing was accomplished. However, if the phase function on the focuser has a large number of breaks, and for coarse discretization of the phase profile, the

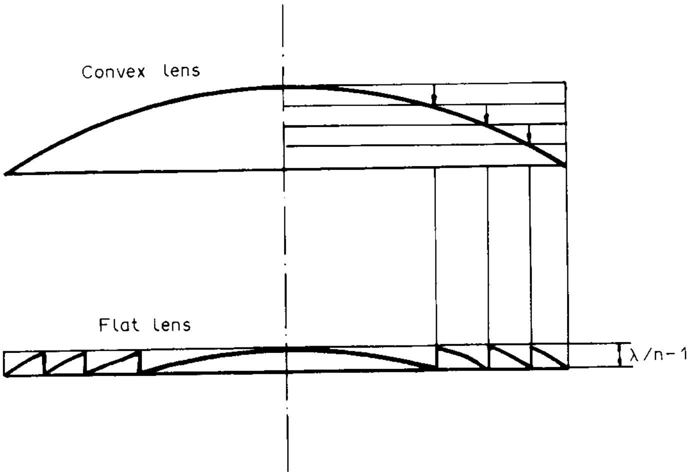

Fig. 3. Production of a kinoform lens.

instability leads to an essential change in the focal line and to a decrease of the focuser's energy efficiency. The inverse focusing problem was first formulated and solved within geometrical optics in [8]. A more rigorous mathematical formulation was provided, together with the elements of focuser construction, in [9], and was followed by a theoretical justification in [10, 11].

2. *Construction of computer optics elements in various wavebands*

The first elements of computer optics—wavefront correctors [12] and focusers [13]—were constructed for the visible spectrum. Nowadays a significant proportion is tailored to the infrared [14], submillimetre and millimetre [15] ranges, for which a series of new automated production techniques have been developed. The first elements were produced by techniques developed in digital holography [16]: the amplitude mask of the phase element, obtained on a multigraded photoresist, was bleached, thereby forming a phase relief over the optical element. This technique was subsequently extended by a photoreduction process of the amplitude mask, resulting in higher spatial resolution.

The first reflecting optical elements—the focusers—were formed by deposition of a metallic film on a glass substrate with a phase relief. Later, focusers geared to perform in a laser environment were manufactured by galvanoplastic techniques [17], in which a complicated phase relief was transferred via the metallized glass onto copper, thus producing a power optical element. By employing binary photoplotters, mask sets were manufactured which were utilized in photolithographic apparatus to produce multigraded phase reliefs [3, 18]. Optical elements in submillimetre and millimetre regions have also been produced on numerically programmed machines.

3. *Study of accuracy characteristics in optical element manufacture*

Although volumes have been written on spherical lens aberrations, the problem is far from being exhausted. When constructing a new optical element, attention must be paid to the parameters determining its precision. This is crucial in the design stage, having regard to discretization and digitization errors of the wave fields in the computer.

In this context we think that the study of the limiting theoretical accuracy [19, 20] holds great promise, in that it defines the "possible" and the "impossible" in computer optics. This imposes fundamental limits on production technologies, and forces one to reject expensive and futile attempts to design elements with characteristics lying within the "forbidden" region.

4. *Computer-aided design and experimental study of computer optics elements*

The computer assisted production of flat optics elements is a complicated process. It comprises the solution of an ill-posed inverse problem, and requires the use of optoelectronic recording devices, as well as the utilization of diverse techniques to produce phase reliefs. Each stage has a distinct effect on the quality of the optical element, and it is hard to predict in advance such characteristics as the focusing linewidth, the energy efficiency of focusers, or the diffractive effectiveness corresponding to a set of transverse modes. The computer-aided production of an optical element is therefore an iterative process: the element's parameters are evaluated at each production stage and improvement strategies can be developed as one goes along. This situation is typical of design processes in general, and computer-aided design in particular. A particularly important role is thereby assigned to the experimental analysis of element parameters. In computer optics two types of experiments are relevant, namely, numerical and actual experiments—both employing the computer—the former by definition, the latter on account of the large information content of the object studied, and the complexity of the optical image processing.

Numerical experiments consist of the following. Suppose the focuser phase function obtained as the solution of an inverse focusing problem is stored as a number array in the computer memory. In order to be able to solve the inverse problem and predict the characteristics of the focuser being produced, one does not actually have to make it right away into an optical element and carry out real experiments on it in an optical system. Such a test could only come at the conclusion of all the manufacturing stages. Of course, we should ascertain the efficiency, or otherwise, of the focuser being produced, but without having to carry out detailed studies of the radiation intensity

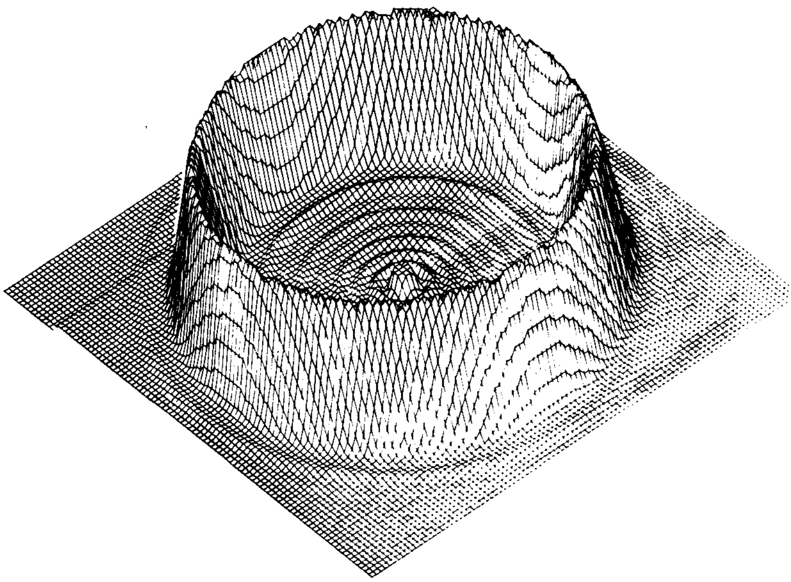

Fig. 4. Computational experiment with an annular focuser.

distribution in the focal region as a function of the phase function derived from the solution of the inverse problem. To get the data we are after, we must carry out an experiment with the set of numbers describing the focuser phase function under construction, that is to say, provide a mathematical solution to the radiation diffraction problem of the appropriate focuser. The output must not be masses of tiresome numbers, but must be presented in a form accessible to experimentalists in optics, namely as halftone intensity patterns on monitors, graphic displays, and compact tables of processed experimental data. It is preferable to work in isometric representations, in colour, of the three-dimensional distributions which arise. Therefore the computer to be used in the numerical simulation should be equipped with suitable graphic and visual display aids in halftone and in colour. It is just this combination of the mathematical capability of solving various diffraction problems, together with the range of visual imaging aids, which allows one to carry out effective numerical experiments in computer optics [21]. Figure 4 illustrates one result of such a computer experiment with annular focuser. In particular, the experiment revealed the existence of an essentially nonremovable spike of intensity at the centre of the annulus, whereby the most intense focusing in the centre of the ring appears in a plane which is at a well-defined distance from the plane of the ring, as measured along the radiation propagation direction. The results of the numerical experiment allow one to optimize the solution to the inverse focusing problem, and to predict the characteristics of the optical elements being designed.

In order to perform real experiments in computer optics one must equip the computer with imaging devices in digital storage. This may be accomplished by various optoelectronic transducers, such as vidicons, photodiode matrices or charge transfer devices. The resulting electronic signals must be converted into digital form and recorded in the computer memory. Technically this can be accomplished without undue difficulties. The principal difficulty is in the digital processing of the optical signals. We encounter again, as we did in the design of optical elements, the problem of machine processing a massive two-dimensional number array, and of solving an ill-posed inverse problem. The solution is complicated by the fact that the two-dimensional signal which is to be stored in the computer memory contains, besides useful information, also errors, distortions and noise. There are many sources for these spurious components: non-uniform illumination of the recorded image, vibrations, strain oscillations in the recording apparatus, quantization of the continuous signal, and so on.

Another problem of automation is the creation of a data base relevant to computer optics problems. At the present time several dozen computer optics of various efficiencies have already been produced. In computer-aided design of computer optics elements there is not enough textual information available. There should also be a store of calculational formulae, blocks of two-

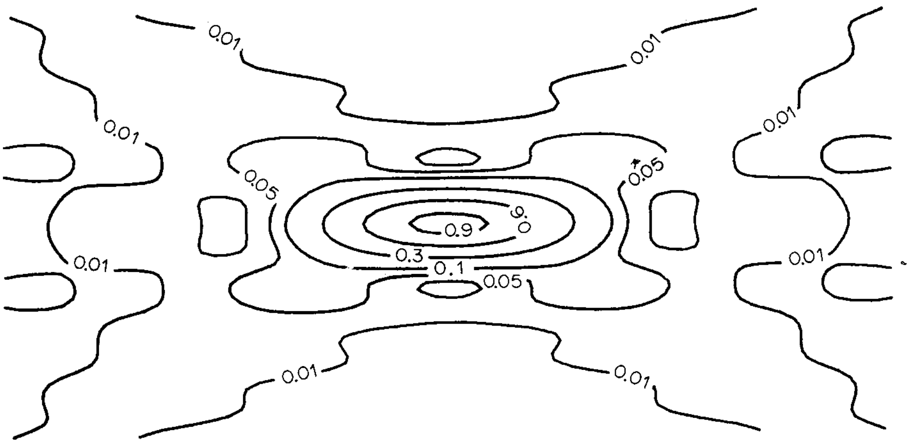

Fig. 5. Lens isophotes.

dimensional data on phase functions of elements, and other necessary information on selected object regions. The creation of such a data base obviously requires the setting up of a specific system of data base management and of designer input language.

5. *Radiation focusers*

The term "focuser" was first introduced [13] in 1981 and was spread by specialists in the field. Sometimes this term is inappropriately employed to describe all elements of computer optics.

We can formulate the problem of focuser design clearly. Thus, Fig. 5 shows the isophotes in the focal region of a lens. It is only an approximation to state that the lens focuses radiation into what is called the focal point. Although it is clear from the figure that the isophotes are bunched near this point, nevertheless there is a complex distribution of light intensity at other points of the focal region. The question arises whether one might produce an optical element that would focus into a focal curve or region with given intensity distributions, rather than into a point, as a typical lens does. This problem was first addressed six years ago. Today we already have an affirmative answer, both theoretical and practical, in the form of a new class of optical elements, the radiation focusers. What do we need these for? First and foremost in laser equipment technology, both in industry and in medicine. A laser without a focuser is only a generator of radiation, while a laser with a focuser is already a piece of equipment dedicated to a specific task, whereas a laser with a set of focusers is already a component of a flexible production system capable of a programmed range of manufacturing operations. But physical technology is not the only application of radiation focusers. The spatial distribution of energy in the focal region of an optical system determines the range of target heating in laser controlled thermodynamic synthesis, and the direction of chemical reactions stimulated by laser radiation. In the manufacture of optical instruments too, one often requires complicated forms of focal curves. At present high diffraction-efficiency radiation focusers can be produced in the visible, infrared, submillimetre and millimetre ranges for various focal lines with tunable intensity along the focal lines. These results have by now become well known from numerous publications [13, 14]. However, there are some technical difficulties in producing focusers in the visible range, associated with deficiencies in image recording devices, as described in [22].

6. *Optical elements used to analyse and generate transverse-mode radiation structure*

This class of optical elements was first produced in 1982 [23] and has already been instrumental in solving a series of interesting problems associated with the application of graded optical fibres [24–26]. The problem of analysing and generating transverse-mode laser radiation structure can be tackled successfully by means of computer-designed flat-optics elements. Each mode corresponds to a definite mathematical function of two variables $\psi_k(u, v)$. The computer forms a two-dimensional number array in its memory to correspond to the k-mode, and the plotter converts these numbers into optical densities on the photosensitive material. The result is a set of flat-optics elements corresponding to the various mode functions. By using these as optical elements, one can construct a device to analyse and form any desired transverse-mode radiation structure.

Now discuss the operating principles of such analysers. Multimode radiation is allowed to fall on a transparency. Its transmission will be determined by the function $\psi_k(u, v)$. The light intensity in the exit lens focus will then be given by the k-mode intensity. By changing the transparencies one can measure the intensities of the various modes, thereby solving the problem of transverse-mode analysis. In practice several mode functions can be accommodated on a single optical element by using holographic methods [27]. If such a transparency is then irradiated by multimode radiation, the intensity of the various modes can be simultaneously measured at various points of the lens focal plane. In fact the device is equivalent to a diffraction grating, analysing the wavelength components by angles.

But actually one has solved a considerably more complicated problem: the transverse-mode radiation components have been separated out by angles. By choosing a set of optical elements corresponding to definite mode functions, we have the means to generate any required transverse-mode laser radiation structure. How does one use this capability in practice? Since the transverse-mode structure in an optical fibre is stable, one can compress the channels for information transmission. This may be achieved by using the various transverse modes as the information carriers. The number of simultaneously excited modes at the optical fibre entrance may vary from several to several dozen. Each mode is a carrier of information and propagates down the fibre independently of the other carriers. At the fibre exit one performs by transverse mode analysis an individual information demodulation for each mode. Mode condensation results in a dramatic increase in the transmissivity of the optical fibre, while the additional demands incurred on the coupling apparatus are not very significant, especially at the receiving end.

It is now appropriate to discuss the meaning of the transverse-mode decomposition of radiation, and to answer the following question: are the transverse modes a mathematician's invention, or does radiation in an inhomogeneous medium actually consist of a series of modes?

A similar question may be posed in discussing the nature of white light: does sunlight really contain a number of monochromatic waves of different colours, or do we merely perform a mathematical summation of sinusoids to produce the observed effect? The modern point of view on the latter question is that spectral decomposition does have a concrete physical meaning when radiation interacts with a spectrally sensitive device, and in that case it does provide an adequate physical representation of the essential physics. The modal expansion of radiation plays an analogous adequate and suitable physical role in the interaction of radiation with mode analysers. Looked at this way, the transverse-mode radiation analysers constructed out of computer optics elements represent a fundamental step from mathematical abstraction towards a physically adequate representation of radiation in an inhomogeneous medium as a superposition of transverse modes. It is noteworthy that such a step could only have been taken with the help of the computer. Nature has not provided us with generators of reference transverse modes to parallel generators of monochromatic radiation. Similarly, there are no prisms or diffraction gratings capable of transverse-mode analysis. Computer optics has therefore filled a fundamental gap by creating synthetic etalons of physical quantities from their mathematical models. It is of course entirely possible that new physical effects will be discovered to enable these devices to be produced without the aid of computers. However, that will in no way influence the value of the role played by computer optics in the analysis and formation of transverse-mode radiation structures.

7. *Construction of wavefront correctors*

The immense possibilities in optical element design opened up by computer optics allows one to construct wavefronts of any given shape. A number of such elements are compensators [12]; namely, elements which transform a plane or spherical wavefront into one with an arbitrary degree of asphericity. The basic task of compensators is thus the control of optical surfaces. In this role a compensator generates an etalon wavefront in interferometric studies of optical surface manufacture, or plays the role of a "zero lens", reducing an aspherical to a spherical problem and enabling one to employ shadow control methods.

By employing special automated techniques, a whole series of compensators have been constructed, specially designed to control spherical surfaces [28]. The construction of solid aspherical compensators remains an unsolved practical problem. It requires the creation of a new generation of high-precision machines with programmed trajectories of the slave mechanism's motion. Theoretical studies [29] of the limiting accuracy have shown that it is possible, in principle, to design optical elements which generate aspherical wave fronts with an error of the order of $\lambda/100$ in the visible region.

8. *Design of spatial filters for optical information processing*

Dozens of articles have been published on hybrid optical-digital processors [4]. But so far these have not been widely applied in information processing (and in particular, image processing) systems. There are several objective reasons for this. First of all, optical processing is inferior to digital in terms of accuracy and universality, as the presence of a large number of mechanical elements in optical processors makes them unstable in operation. Also the problem of effectively coupling optical and digital processors has not yet been solved. But if we recall that the execution of a two-dimensional Fourier transformation involves the considerable expense of a high-performance computer system, whereas an optical processor would perform the same task in real time, one can understand the amount of research effort devoted to this promising field.

In this context we perceive as especially promising developments the construction of Bessel-optics elements [30], elements transforming cartesian into polar–logarithmic coordinates [31], and programmed diffraction gratings [32].

9. *Design of kinoform lenses and "aberration-free" objectives*

The solution of these problems has great practical value. Great practical progress has been made in designing large aperture kinoform lenses [3]. "Aberration-free" objectives have been reported containing several kinoform lenses and possessing excellent mass-size characteristics [33].

10. *Solution of scientific, technical and medical problems through application of computer optics elements*

Computer optics has its origins in the demands of a whole series of human endeavours, primarily of problems in physics, optical instrumentation, laser technology, fibre couplings, and so on. Thus, it is completely natural that computer optics elements can be used directly to solve a wide variety of problems. A series of examples illustrating this statement have been given in previous sections. We would like to emphasize another circumstance. Computer optics elements are likely to have a revolutionary effect, especially in laser technology. The application of focusers allows one to perform "instant" eye operations [34], as well as to develop completely novel material processing technologies in industry [35]. The application of optical elements to the analysis and generation of transverse-mode structures in fibre optical transmission lines and detection equipment holds out enormous promise. In order to develop the applications of CO one must acquaint scientists and specialists from different scientific, technical and medical disciplines with the potentialities of computer optics.

HORIZONS OF COMPUTER OPTICS

The role of computers in optics is far from being exhausted by problems associated with the design of the flat-optics elements we have considered so far. The material of this survey was naturally dictated by the scientific interests of the authors, and the desire to throw light on the revolutionary role of computers in the ancient science of optics. But the computer's influence in optics is felt in many directions. Firstly, computational optics has been established as a branch of optical instrumentation, solving design problems by applying computers to optical systems satisfying image forming quality requirements. Interestingly, computational optics developed long before the advent of computers, in the context of designing high-quality camera objectives. The application of computers in computational optics has allowed one to address problems of automated design of variously dedicated optical systems: astronomical telescopes, microscopes, projection equipment, camera objectives, etc., using available optical elements like lenses, prisms, mirrors, and so on. We note that the inclusion of flat-optics elements in this list results in a considerable broadening of the functional possibilities of a whole series of optical systems.

Secondly, digital holography is being actively developed. Thirdly, technical detection systems have been developed imitating the efficiency of living organs, providing information on the surroundings in terms of the light absorbed by them. The presently available technical vision devices have a rather low information yield and are basically digital systems close in spirit to digital optical image processing systems. They have not achieved all the optical possibilities of the eye, nor have they attained optical information processing capable of shape identification. However, there is no doubt that in subsequent generations of technical vision, computer optics elements will assume a considerable role, fulfilling key functions of optical signal analysis and processing.

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