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Presentation

Central Optical Laboratory, Department of Physical Optics, Warsaw, Poland

Last five years of scientific and research activity

In fact, Central Optical Laboratory in Warsaw is an institute of applied optics. Its activity includes different fields of classical and modern optics with special emphasis on optical systems (theory, design, evaluation), technology of optical elements, thin films, electrooptical crystals, holography and holographic interferometry, light microscopy, microinterferometry, optical processing and Fourier optics, optical waveguides and gradient-index optics, unconventional optomechanic and optoelectronic instruments. At present, it incorporates six research departments, a centre of scientific and technical information (in the field of optics), and mechano-optical workshop.

This report presents the activity of the Physical Optics Department alone. There is a certain continuity; the objects of the Department are, in the first place, research and development in optics orientated toward applications in practice. The Department has a staff of experienced researchers, most of which graduated in physics and engineering optics, several holding a Ph. D. degree. Head of the staff is the author of this report, holding a scientific title and scientific position professor.

The recent research projects dealt with optical waveguides, gradient-index optics, diffraction and scattering of light, Fourier optics, holography, interferometry (both classical and holographic), microinterferometry, optical microscopy, and spectrophotometric instrumentation.

It is also worth-while mentioning that the Department was active in education and training of engineers and scientists in optics. Six persons from other institutes their Ph. D. theses prepared fully or partially in this Department. These theses dealt with holographic microscopy and holographic microinterferometry applied to biological research (three-dimensional analysis of movement in *Physarum polycepharum* plasmodia, and holographic microscopy of glycerination of *Amoeba proteus*), holographic interferometry applied to testing the shape of surfaces of machine elements, pulse and double-pulse holographic analysis of oil-mist, determination of refractive index profiles by using double-refracting transverse microinterferometry.

On the other hand, the Department has very close collaboration with the Institute of Biostructure of Warsaw Medical Academy (field of cooperation: optical diffractometry in biomedical research), Fryderyk Chopin Academy of Music in Warsaw (studies in foniatry by using double-pulse holographic interferometry), Reseach and Development Centre of Medical Technique ORMED (spectrophotometry for biomedical purposes), and with other research institutes and high schools.

Below a short characteristic of main scientific and research works done at the Physical Optics Department of the Central Optical Laboratory is given. At the end of this report, a list of selected publications (papers, review articles, books) by the researchers of this Department is added. Some papers done with cooperation with scinetists and researchers from other institutes are also included. The cooperating co-authors are marked by asterisks (*).

Optical waveguides and gradient-index optics

The research in the field of optical waveguides (planar and fibre waveguides) was undertaken in the late seventies and has been carried up to date with increasing interest. In the earliest stages, scientific and research works were conducted with the aim to produce and optimize a planar waveguide based on materials and technology at hand. This yielded in obtaining SiO_x thin waveguiding films on glass substrates [1]. Problems of waveguide quality and possibilities of non-ideal waveguide theory application to the surface testing were considered as well [2], [5]. Interesting research on the guided waves application to holography was also carried out, which resulted in obtaining evanescent wave holograms in a photoresist layer [3], [4].

Other area of interest concerns the planar waveguide lenses, starting from the aberration analysis [8], through the technology investigations [10], [11], up to the sophisticated analysis of the Luneburg lens problem, and the applications of GRIN lenses to the integrated optics. The main achievements in the Luneburg lens theory were the analytical solution of the Luneburg equation and its simplifications, and the derivation of a new family of multiple-foci Luneburg lenses [9], [12]–[15], [16]–[19]. Recent works in the waveguide lens theory concern the geodesic lens profile and the analysis of non-ideal profile manufacturing influence on the lens performance.

The investigations in the Luneburg lens theory constitute a link between integrated optics and the gradient index optics. Apart from the spherical gradients, the cylindrical index profiles are subject of more detailed analysis and especially the image transmission through GRIN rods [20]–[24]. In this area a close co-operation is maintained with the Optics Department of the University of Santiago de Compostela (Spain).

Quite recently, a perfect geodesic lens designing has been proposed [25], [26], and new generation of planar waveguide Luneburg lenses, developed theoreticaly by J. SOCHACKI, has been realized in practice by a group of researchers at the Technical University of Wrocław [27].

It is also worth-while to note that the accurate reconstruction of the refractive-index profile of optical fibres and preform rods has been formulated on the basis of transverse interferometry data [28]. The theoretical analysis has been verified in practice with successful results.

Fourier optics and optical processing

Different problems of Fourier optics and of optical processing were investigated mainly by M. DASZKIEWICZ and J. GALAS. Among other things, perturbations of the optical Fourier transforms of transparencies, caused by phase noise [29], effect of the size of incoherent light sources on spatial filtering the images [35], and methods of suppresion of some unwanted structures adherent to the processed images were studied. It is worth-while mentioning that a simple technique for removing a line raster from optical pictures (e.g., photographs of TV-images) was developed [31]. The technique depends on moving the processed picture during a copying process; the movement of an oscillating form at right angles to the raster lines appeared to be the most effective. An optimum oscillation amplitude was found for which both the contrast and resolution of the final image are as good as those of the original image, but the former is free from the unwanted raster.

An universal laser diffractometer was designed, built, and installed in the Fourier optics laboratory. This installation was and is permanently used for the structural analysis of different objects and scenes recorded on photographic plates. Especially, it is largely used for biostructural research with cooperation with the Institute of Biostructure of the Medical Academy of Warsaw [30], [36], [37]. Up to the present, the following problems were studied:

i) ultrastructural changes occuring in cells in the course of in vitro transformation,
ii) structure of peripheral nerves in the process of degeneration and regeneration,
iii) structure of bone tissue in physiological conditions and in some systemic diseases of the skeleton.

Some cooperation was also performed with the Technical University of Mining and Metallurgy in Cracow for which a portable laser diffractometer was provided for studies of solids by using electron microscopy [34].

An accurate analysis of spatial frequencies requires very well corrected lenses, and the diffraction pattern must be sampled by means of a moving detector or a stable multiple-detector array strictly in the Fourier plane. To overcome this limitation, a new sampling method has been developed [38]. In this method a single stable detector is placed at the rear focus of a Fourier transform lens, while the sampled diffraction pattern is moved over the Fourier plane. The movement of the diffraction pattern can be obtained when the analysed image is illuminated with a parallel light beam whose inclination is changed with respect to the optical axis of the Fourier transform lens. An opto-mechanical device enables the diffraction pattern to be sampled along the Archimedean spiral trace, thus light intensity distribution can be recorded as a function of polar coordinates. According to this principle, two compact diffractometers (prototypes) were constructed, one of which has been installed in the Institute of Biocybernetics and Biomedical Engineering of the Polish Academy of Sciences (Warsaw) and the other in the Central Institute of Geodesy and Cartography (Warsaw).

Light scattering

Laser light scattering was applied by W. CHABROS to surface quality characterization of flat and slightly curved optical elements. A developed technique may be qualified as a semi-total integrated scattering method by contrast to the known TIS (Total Integrated Scattering) method which was developed by Jean and Harold Bennett and their co-workers at Michelson Laboratory, China Lake, California. Instruments designed according to the TIS method use a spatially filtered and collimated He-Ne laser beam incident on the sample via an opening in the vertex of a semi-sphere mirror (Coblentz mirror). Light specularly reflected from the specimen under study leaves the instrument via the same opening and is absorbed by a light trap. Part of the incident light is scattered by the surface micro-roughness, thus diffusely reflected light occurs. The latter is retroreflected by the semi-sphere mirror and focused back onto a small detector positioned adjacent to the examined surface. The intensity of scattered light recorded by the above-mentioned detector gives a measure related to the surface micro-roughness. No Coblentz mirror is used in a recent version of the instrument developed by W. CHABROS for assessing the quality of polished glass surfaces. This instrument also uses a spatially filtered He-Ne laser beam, focused obliquely on the surface to be tested. The light spot on the surface can be varied. Laser light specularly reflected from the examined surface passess via an opening in a flat mirror, while light scattered by the surface micro-roughness is reflected by this mirror and directed, via an objective of suitable numerical aperture, to a photomultiplier, whose reponse is proportional to the intensity of scattered light accepted by the objective mentioned above. The instrument incorporates an additional optical system enabling the surface under study to be visually observed under some magnification. This instrument has appeared to be very useful for testing polished surface of flat and slightly curved optical elements and is now offered for other users (three prototypes were purchased by Polish Optical Works — PZO, Industrial Centre of Optics — PCO, and Institute of Technical Physics of the WAT).

Holography and holographic interferometry

Both theoretical and experimental studies of the elimination of coherent noise from holographic images were continued (for the interested readers more details, regarding this problem, may be found in Optica Applicata **4** (1974), 42–47). A deep theory of the time everaging method applied to coherent noise suppression was formulated and experimentaly verified by R. PAWLUCZYK; the detailed results are presented in his excellent doctorate thesis.

An improvement of the quality of holographic imaging by using the method of noncoherent superposition of holographic images was also proposed [40].

Simultaneously, a highly coherent pulse ruby laser was developed and a versatile laboratory sut-up for pulse holography and double-pulse holographic interferometry was installed [39]. This sut-up was and is still permanently used for different scientific and engineering studies in various fields of science and technology (automotive units and components [44], energetic aerosols, oil-mist). The most sophisticated studies have been performed in the field of foniatry. Vibrations of epiphysis surface (skin on neck and face) of singers during singing have been examined in detail by using double-pulse holographic interferometry [41], [45], [46]. Soft palate of healthy persons and different pathologic cases of vocal organ have been also investigated. The obtained results show that double pulse holographic interferometry can be qualified as an useful tool for the study of the mechanism of sound creation in human vocal organ. During the foniatric studies it has been stated that diffuse illumination of the object under examination pemits us to identify the zero-order interference fringes or nodal regions of the vibrating surface [42], [43], [47]. For the interested reader many details regarding these and other related problems may be found in the Ph. D. thesis *Application of double-pulse holographic interferometry to phoniatric studies* by Z. KRASKA.

Experimental research in the field of technology of holographic diffraction gratings was carried out during a few years by M. SZYJER, and we are now able to manufacture both concave and plate reflecting holographic gratings for spectrophotometers [48], fibre multiplexers and demultiplexers [79], and other spectral instruments.

Further research by using the holographic interference microscope with coherent noise suppression, which was built 10 years ego, has been continued. For instance, this instrument has quite recently been used for investigation of crystal dissolution [49] with the emphasis directed toward the crystal-solution interfacial layer during the dissolution process. The use of the reference laser beam, inclined with respect to the object beam, permits one to obtain interference patterns whose fringes show clearly the depedence between the refractive index of solution and the distance from the dissolving crystal. It has been stated that a strong influence of convection, even in a 1 mm thick cuvettes, on the dissolution process occurs. It has also been found that thermal effects involved during dissolution do not effect significantly the shape of interference fringes. In conclusion, the authors state in their paper [49] that the used holographic interference microscope is a valuable tool for investigations which permit us to understand better the mechanism of growth and dissolution of crystals.

Interferometry and microinterferometry

Subjects of activity in this field are quite well characterized by titles of the listed publications [52]–[72]. In particular, microroughness of both cylindrical [52] and flat surfaces [58] was investigated by using a double-refracting interference microscope. It has been stated that differential interference contrast (DIC) microscopy with variable wavefront shear (VADIC) is more suitable than the Nomarski DIC system for the study of smoothly polished optical elemements and semiconductor wafers [58].

The studies of injurious effects in microinterferometry of textile fibres, caused by spectral dispersion of the refractive index and of birefringence have largely been performed [53] and some practical conclusions have been drawn, which permit us to measure more precisely the directional refractive indices and birefringence of textile fibres, especially polimeric fibres. The usefulness of standard interference filters in visual microinterferometry has also been examined [55]–[57], as well as microinterferometry with variable wavefront shear has been proposed for the determination of the refractive profile of optical fibres [59]. Studies in the latter field have been continued by M. BOŻYK (Technical University in Białystok) and the results are in detail presented in her doctorate thesis. Quite recently, the theory of transverse interferometry of cylindrical objects has been refined by J. SOCHACKI [28] who has formulated an exact approach to reconstruction of the refractive index profile of optical fibres. Up to now, only approximative solutions, mainly based on the theory given by two Japanese researchers, K. Iga and Y. Kokubun, were in use.

Some general aspects of accurate interferometric measurements by using relatively simple means were also studied and then discussed in a series of papers dealing with variable wavelength interferometry (VAWI). Three versions of the VAWI method have been developed and experimentaly verified [60]–[71]. The VAWI–1 technique [60], [62], [69], [71] depends on selecting such paricular wavelengths $\lambda_s = \lambda_1 > \lambda_2 > \lambda_3, \ldots$, for which interference fringes displaced by an object under study become consecutively coincident and anticoincident with the reference (undisplaced) fringes; thus, interference order increments $q_s = 0, 0.5, 1, \ldots$ are observed. This technique is suitable for studying the objects which produce optical path differences (δ) larger than several wavelengths, say, $\delta_1 > 3\lambda_1$. On the other hand, the VAWI–2 technique is suitable for determining $\delta < 3\lambda_1$. This technique [63], [65] uses two parallel pointer lines in the image plane of the interferometer. The zero-order fringe of the empty interference field is adjusted to the coincidence with one pointer line, and high-order fringes displaced by the object under study are consecutively brough into coincidence with the other pointer line when the wavelength of monochromatic light is continuously varied. The VAWI–3 technique [64], [70] is similar to VAWI–1, but uses a single pointer line and does not require simultaneous observation of the reference and displaced interference fringes.

A specific feature of the above techniques is a fact that the only parameter which is directly measured is the interfringe spacing (*b*). This quantity can be known very accurately as the distance $l = 20b$, $40b$, or even $100b$ is measured rather than a single interfringe spacing *b*.

The VAWI techniques mentioned above have permitted us to formulate an idea of a specific interferometric method referred to as object-adapted variable wavelength interferometry (OAVAWI). Its general principle has been given in the paper [67], while a more complete theoretical basis and large experimental verification will be given in a series of article which are now prepared for publication.

It is also worth mentioning the double-refracting interferometer with variable direction of tilt of laterally sheared wavefronts for testing microscope objectives. This instrument uses polarized light and two birefringent elements: a symmetrical Wollaston prism, located in the image plane of the objective under test, and a birefringent fibre, which is placed in the objective object plane. The Wollaston prism produces a lateral wavefront shear, while the fibre is used as a secondary light source of slit size, which together with a rotatable condenser slit diaphragm produces variable directions and amounts of tilt of laterally sheared wavefronts. Below the condensor slit there is a polarizer which is crossed with an analyser positioned behind the Wollaston prism. Additionally, this prism is preceded by a polaroid crossed with the subcondenser polarizer. An interference pattern and so wave aberrations of the tested objective are observed in the objective exit pupil [54].

It has been stated that interference fringes are asymmetrically distributed in the image plane of some double-refracting microinterferometers commercially available [72]. This defect is especially produced by typical birefringent Wollaston prisms and is responsible for some errors in the measurement of optical path differences. In particular, the errors arise when the interfringe spacing is directly measured in the image plane or determined from an interferogram recorded on a photographic material. This defect can be overcome if the symmetrical Wollaston prism is used.

Light microscopy

First of all, a simple polanret phase-contrast system has been developed [74]. It uses only a single polaroid ring instead of three zonal polarizers as requires the original polanret system developed by H. Osterberg and manufactured by American Optical Corporation. It is therefore selfevident that the new system is much more easy for manufacturing and its economy of light is three times better, but also needs easily accessible exit pupils of microscope objectives, where the polaroid ring must be located. This ring is, of course, conjugate with an annular opening of the condenser diaphragm, preceded by a quarter-wave plate and polarizer, and followed by an analyser. Both the polarizer and the analyser are rotatable.

An interesting effect was noticed when some experiments in the field of optical Fourier transform microscopy were carried out, namely it was stated that a birefringent fibre, oriented diagonally between two crossed polarizers of a polarizing microscope fitted with a slit condenser diaghragm, can be considered as a single-, double- or multiple-slit object if the condenser slit diaphragm is parallel to the fibre axis (the fibre is, of course, on the object stage and the microscope is focused or nearly focused on it). When the birefringent fibre is transilluminated, via the substage condenser, by monochromatic light, it produces a specific interference pattern in the exit pupil of the microscope objective. This pattern manifests itself as an optical Fourier transform whose interesting features can be used, e.g., for measuring the fibre birefringence or spectral dispersion of birefringence if the light wavelength is continuously varied, as well as for testing the homogeneity of cylindrical polymeric fibres.

A new sceanning device was developed by T. Kozłowski for microdensitometry of biological cells and tissues in the image plane of the transmitted-light microscope. In its basic fragment the device consists of two rotating opaque plates with crossing slits of Archimedean spiral shape. When the plates rotate with different speed, a square aperture resulting from crossing spirals scans the object image along the *x* and *y* axes [77].

Two specific portable microscopes were constructed for testing optical fibres [79], [81], [82]. One of them belongs to the reflected-light DIC systems and serves for testing cross-sections of optical fibres [81]. It uses polarized light and birefringent prism like the Nomarski DIC system. Very fine irregularities and surface defect of fibre cross-sections are observed, thus this instrument permits us to prepare and accept for connections such two fibres whose face surfaces are perfectly flat, smooth, and free from cracks and other defects which attenuate energy of guided light waves.

The other of the above-mentioned microscopes incorporates two low-power objectives, whose axes form an angle of 60°, and serves for testing the quality of welding of optical fibres. It is attached to the fibre welder. Two images of the welded region are observed side by side in the bisected field of view of a single eyepiece. Such a two-sided observation enables the fibres to be welded extremely coaxially.

Conclusion

As can be seen from the above review, the field of activity was rather large and not restricted strictly to physical optics. Anyway, the border lines between various branches of optics are now blurred, and even a common light microscope is an instrument in which there reside and successfully operate perhaps the most fascinating phenomena of physical optics, namely, the diffraction, interference, and polarization of light. This line of activity is continued.

List of selected publications

Optical waveguides and gradient-index optics

1. MANASTERSKA A., CHABROS W., KOPEĆ G., PLUTA M., *SiO_x thin film as a planar waveguide.* 2nd National Symposium *Waveguides and Their Applications*, Jabłonna 1979, Vol. 2, pp. 340–347 (in Polish).

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