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Presentations

Institute of Technical Physics, Jarosław Dąbrowski Military Technical Academy, Warszawa, Poland

The Group of Waveguide Optics headed by Prof. Mieczysław Szustakowski works as a part of the Institute of Physics, Military Technical Academy, Warsaw. Its research program includes:

— *acoustooptics,*
— *integrated optics,*
— *waveguide optics.*

Acoustooptics programme is realized under the sponsorship of the M.R.–I.24 Program, which is supervised by the Institute of Fundamental Problems of Technology, Polish Academy of Sciences (IPPT PAN) in the frame of the project *Application of the acoustooptic devices in laser techniques*. The group works on technology of piezoelectric transducers of 10–1000 MHz working frequency. The technology will be based on the solid materials transducers such as $LiNbO_3$, $LiJO_3$, SiO_2 cemented to the glass, or single crystal acoustooptical cells that are to be employed. The design and production of acoustooptical modulators working in visible-to-10.6 μm range constitute another branch of activity. The actual research works concern the method of such modulator excitation which would assure a wide working range, and the method of cooling enabling the use of the high excitations powers (above 1 W).

The group takes part also in the works concerning the following application of modulators:

— internal modulation of light in laser resonators (the so-called Q-switched modulators — stimulating the pulsed action of the gas and solid lasers),

— external modulation in lasers of various types as well as in devices employing coherent light,

— acoustooptics devices to process the signals of radio frequency, especially for spectrum and correlation analysis of signals.

A special achievement of the group was the elaboration and production of the modulators applied to pulsed lasers and to a model of optical printer.

Besides, within the same Institute of Technical Physics in a group headed by Prof. Józef Żmija a subgroupe is active in producing the single crystals of pure BGO and BSO, both pure and doped by transient elements (Fe, Cr, Mn) as well as single crystals of TeO_2, P_6MoO_4, $LiJO_3$. The other materials used in the acoustooptic group are single crystals of quartz, and quartz and optical glasses.

In the frame of integrated optics field the group participates in the P.R.–20 (IF, PAN) Program in the project *Elaboration of physical and technological fundamentals of the needs of integrated optoelectronics* (the leader of this project is Prof. Bohdan Paszkowski). Actually the research works are concentrated on mastering the production technology of planar optics elements such as: planar lightguides, stripe lightguides, periodic structure, and planar modulators. The said elements on the single crystal lithium niobate substrate are a speciality of the group within this program. The achievements of an over 30% light modulation effectivity of Bragg type in diffusion planar $LiNbO_3$ lightguides by means of the acoustic surface wave at 140 MHz frequency is a success of the group. The group has at its disposal the systems of vacuum technology as well as photolithography devices which enable to realize the accepted program of works. Besides, a laboratory measurement system has been elaborated to examine the properties of transmission structures of planar optics, such as number of modes, losses and focusing.

In the frame of optic lightguides field the group participates in realization of the program led by the Institute of Communication specializing in elaboration of the lightguide short-range lines. The research works concern the transmission of the analog and pulsed modulation signals and TV signals by means of the gradient lightguides and thick-core lightguides of clad-polymer type. The elaboration and production of the lightguide transmission line for the TV signals as well as realization of heterodyne detectors (laboratory system) of signals of analog and pulsed modulation by employing acoustooptic modulation in the transmission branch of lightguide interferometers are the main achievements of this group. The group works also on application of lightguides as gauges to measure the physical fields (acoustic, for instance) by developing the phase detection system based on interference phenomena and single mode lightguide. Hence, the problems of polarization and coherence transfer in cylindric lightguides become the subject of interest. The research works are also devoted to self-focusing lightguides of selfoc type.

The group has at its disposal a laboratory measurement setup to examine the properties of cylindric lightguides which allows the measuring of the distribution of refractive index dispersion and attenuation by the method of back scattering.

In the fields of lightguide production technology, light sources and photodetectors the group cooperates with the Maria Skłodowska-Curie University in Lublin (Poland) and the Institute of Electron Technology in Warsaw (Poland).

The research works performed in the group were published in such journals as Optica Applicata, Journal of Technical Physics, Archiwum Akustyki, Biuletyn WAT, as well as presented at the following conferences and symposia: Symposium of lightguide measurement techniques (Lublin 1981), Symposium on non-telecommunication lightguides (Białystok 1982), Conference on lightguides and their applications (Jabłonna 1983), and II School on acoustooptics (Gdańsk-Wieżyca 1983).

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Mieczysław Szustakowski

Laboratory of Optical Spectroscopy of Semiconductors, Department of General Physics, Institute of Physics, Jagiellonian University, Kraków, Poland

In 1965 the Laboratory of Optical Spectroscopy of Semiconductors was initiated within the Department of Experimental Physics directed by Prof. Henryk Niewodniczański, who in those days performed the duties of the head of Department and the Director of Institute of Physics of Jagiellonian University. Eight years later, in 1973, this Laboratory was transferred to the Department of General Physics of the Institute and has remained there up to now. The Laboratory numbers now 10 physicists, mainly young doctors (6 persons) and 2 technicians. In the years 1980–83 the members of the Laboratory published or prepared for publication 39 papers. The first main interest of the group that originated in 1965, was the study of fundamental reflectivity spectra of semiconductors in room and liquid nitrogen temperatures. Next, beside the direct measurements of reflectivity coefficient, electro- and thermomodulation techniques were also introduced.

It is well known that fundamental reflectivity spectrum of semiconductors contains important information on electronic structure of the semiconducting materials and can be used to verify the theoretical models of band structures. By adapting Kramers-Kronig relations, the reflectivity coefficient measured in wide energy range of incident light can be applied to calculation of the real and imaginary parts of complex refraction and dielectric constants. An application of the fundamental reflectivity spectra to analysis of the crystalline properties of solids seems to be a tool sufficient for the description of the real structure of semiconducting materials, whereas the analysis of reflectivity spectrum in infrared, visible and near ultraviolet regions supplies important information on parameters defining the roughness of surface. The above investigations require precise measurements of the reflection coefficient in wide energy range, which can be achieved by the use of very sensitive and highly specialized equipment. The respective facilities, which fulfil the above conditions were built by us with financial support of The Institutes of Physics of Jagiellonian University and Polish Academy of Sciences. One- and two-beam reflectometers with automatic data recording* have been built on the basis of Carl Zeiss SPM-2 and Hilger and Watts E 766 monochromators. Using the home-constructed set-up one can measure the reflectivity coefficient in 0.3–11 eV energy range, i.e., from about 4–0.12 μm. Now final tests with CAMAC system are being in

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progress. This system will enable permanent measurements of reflectivity coefficient using the reflectometers we have already constructed and computers MERA-305 and MERA-60.

In the years 1980–83 the research activity included the following branches of the Solid State Physics:

1. The experimental and theoretical studies of electronic structure of semiconductors and metals.
2. The studies of the real crystalline structure of materials.
3. The studies of the roughness of dielectric, semiconductor and metallic surfaces.

Experimental studies of the electronic structure of solids

During the last three years the investigations of electric structure were mainly focussed on the measurements of monocrystalline semiconductors as well as polycrystalline thin films in 0.3–0.5 eV energy range and at various temperatures (100–300 K). Theoretical investigations of band structure model of the chosen semiconductors and metals were also performed.

The main results are as follows:

i) The studies of fundamental reflectivity spectra for $Cd_xHg_{1-x}Te$ monocrystals (papers: 6, 9, 16, 36).

For these materials the dependence of fundamental reflectivity spectra on temperature and Cd concentration were investigated in 1.7–8.5 eV energy range. The thermal coefficients versus composition were determined for several maxima observed in fundamental reflectivity. Based on these results and the published theoretical and experimental data an identification of the analysed transitions was proposed. In particular, the transitions observed in 6–8.5 eV energy range were identified as those between the valence and higher conductivity bands.

ii) The studies of reflectivity spectra of monocrystalline, polycrystalline and amorphous Cd_3As_2 (papers: 3, 21, 22, 23, 31).

The results obtained were compared with other experimental data and interpreted on the basis of Lin-Chung band structure model. In this investigation the roughness of various samples was taken into account and discussed.

iii) The studies of reflectivity spectra of $A^{I}B_2^{III}C_4^{VI}$ ternary compounds (24, 36, 37).

The results were analysed and critically compared with the literature data. These complex investigations allowed us to understand better the electronic structure of these ternary compounds and to distinguish several classes of electronic interband transitions (the classes A, B, C). In case of $A^{I}B^{III}C_2^{VI}$ compounds a simple model for energy transitions between 2–4.5 eV was proposed.

iv) The studies of $A^{II}B^{VI}$ mixed compounds with manganese (papers: 13, 33, 39).

In the last years the interest of many laboratories has been focussed on the investigations of the II–VI mixed compounds with manganese. The reflectivity spectra of $Cd_{1-x}Mn_xTe$ and $Zn_{1-x}Mn_xSe$ and reflectivity and absorption spectra of $Zn_{1-x}Mn_xS$ were studied in the 0.7–8.1 eV energy range. The results were compared with the experimental data. For all these compounds we found very distinct anomalous influence of Mn content on the shape of reflectivity spectrum. It has been confirmed that characteristic fundamental reflectivity spectrum structure of II–VI compounds vanishes with the increasing Mn content. To complete the experimental and theoretical information about CdTe-MnTe system, the absorption and reflectivity spectra have been recently measured for polycrystalline bulk and thin films of MnTe in 0.05–8.5 eV energy range. The investigations being continued.

v) The studies of CdF_2 reflectivity spectra (paper 7).

Investigations of the reflectivity and absorption of light for CdF_2 in 6–8.5 eV energy range at various temperatures (100–300 K) are also an important field of research. An anomalous temperature dependence of the intensity of the excitonic transition near 7.5 eV found for CdF_2 seems to be a very interesting effect and the one not clearly explained till now. Further investigations are continued.

Theoretical studies of the electronic structure

(papers: 2, 10, 14, 28, 29, 30, 34, 35)

The investigations carried out included the following problems:

i) The earliest one was the theoretical description of the band structure and peculiarities of the optical properties of $Cd_xHg_{1-x}Te$ alloy. In the paper 2 and in the previous publication (Solid State Commun. **32** (1979), 413) the authors have shown that simple tight-binding approach gives a good description of the optical spectra of the alloy and explains in part the anomalies observed experimentally in those spectra.

ii) More recently, a new method has been developed for quick and efficient calculation of the band structure of systems containing both localized (*d*-like) and delocalized electrons (paper 14). That method employ mixed Gaussian-type orbitals and plane wave basic set of functions. Crystal potential was expanded in terms of rather sophisticated Fourier series providing extremely quick convergence. All the matrix elements were calculated analytically.

The method tested already for both semiconductors and magnetic metals, proved to be a powerful tool for the calculation of the electronic structure of solids containing paramagnetic atoms. At the same time the band structure calculations of the antiferromagnetic MnTe were performed. The results have shown that optical properties of this method can be described in terms of one-electron approach. Also "ab initio" calculations of electronic structure of hypothetic zinc blende MnTe have been finished. It could be used to predict the propreties of the band structure of CdTe-MnTe system. Unfortunately, cubic MnTe turned out to be a metallic structure not very useful for these purposes.

At present the theoreticians from our group have been involved in calculation of electronic structure of manganese compounds, like MnSe and MnSb.

The studies of real crystalline structure

(papers: 5, 15, 17, 18, 27, 32)

The fundamental reflectivity spectra were applied to investigations of real crystalline structures, i.e., to define random distributed internal stresses and distorsion of these crystalline structure. In case of monocrystalline bulk and thin films of ZnTe, this investigation was devoted to analyse the influence of random distributed internal stress in crystal and distorsion of the crystalline lattice as well as influence of technological conditions of material preparation on electronic structure of those materials. The influence was found to be significant and interpreted in terms of deformation processes. This research program initiated for ZnTe has been expanded for reflectivity spectra of PbTe, SnTe and $Pb_xSn_{1-x}Te$ and Si.

Unfortunately, because of the high sensibility of the surfaces of PbTe, SnTe and $Pb_xSn_{1-x}Te$ samples to the method of surface cleaning, the results for these materials were not reproducible. However, in case of Si monocrystals, for which crystalline structure was distorted by implantation of 70 keV Si ions, the obtained results were excellent and easy for interpretation.

A new very fruitful field of interest is the analysis of the nearest neighbour order in $Cd_{1-x}Mn_xTe$ semiconductor crystals by means of Extended X-Ray Absorption Fine Structure (EXAFS) (papers: 20, 25, 26). These studies were made in cooperation with the Institute of Physics of Roma University and Group PULS (Program of Utilizing of Synchrotron Radiation) in the Institute of Nuclear Physics in Frascati. The results obtained for $Cd_{1-x}Mn_xTe$ seem to be significant. It has been shown that in $Cd_{1-x}Mn_xTe$ Mn does not replace the position of Cd atom but occupies its own position in a little shorter distance with respect to Te atoms (2.75 Å instead 2.80 Å). Another significant result is that the positions of Cd and Mn atoms weakly depend on Mn concentration and that virtual crystal approximation is not enough good approach for $Cd_{1-x}Mn_xTe$.

The studies of the surface roughnesses

(papers: 1, 8, 11, 21, 27)

The light scattered from surface provides information about the relief of surface. From the reflectivity coefficient the basic parameters characterizing the surface roughness can be extracted, i.e. on the basis of Bennett-Porteus approach mean square deviation σ from the mean line and the mean square slope m of roughness can be calculated. For these purposes the measurements of light reflectivity in infrared, visible and near ultraviolet regions have been applied. The roughness of surface has been analysed for crystalline quartz, metallic Al, Cr and Ag thin films evaporated on crystalline rough quartz. In order to support these investigations and to extend the measurements to the region of very smooth surfaces, i.e., to the roughnesses 30–200 Å, interferometric analysis of Fringes of Equal Chromatic Order (FECO) was applied.

While comparing the solution worked out in our Department to that described in literature, two new important improvements introduced in that set-up should be mentioned. These are: special photo-plate compartment and ingenious device for the sample surface scanning. The latter allowed us to investigate the surface topography. Moreover, we have completed a whole set of computer programs used for a detailed interferogram analysis.

The developed method was successfully applied to the investigations of the very smooth surfaces of different type of glass and piezo-quartz plates and Si monocrystalline samples.

Final remarks

In this short presentation of the main directions of the research activity of the Laboratory of Optical Spectroscopy of Semiconductors, the advantages of cooperation with other research centres should be stressed. Since in our Laboratory there is no group for sample preparation, all our studies were performed on the samples produced in several national and foreign technological laboratories. That is why the results obtained with the use of samples produced in various laboratories could be easily compared and the real structure of materials analysed. In the future this type of cooperation concerning the analysis of electronic structure will be continued. Our Laboratory is also in close and very fruitful cooperation with the Institutes of Physics of Rome I and II Universities and Institute of Nuclear Physics in Frascati (Laboratori Nazionali di Frascati) by participating in the Program of Utilization of Synchrotron Radiation (PULS). Using EXAFS this cooperation resulted in new and very interesting results concerning the near order structure of the crystalline and amorphous solids. From the reflectivity measurements the important information about optical properties of solids in far vacuum ultraviolet (10–40 eV energy range) was also obtained. These branches of investigations are to be continued. Moreover, new fields of investigations, complementary to the experimental and theoretical program realized up to now in the Laboratory, are proposed. These investigations include photoconductivity and integral and angular photoemission of electrons. They allow a better understanding of electronic structure of solids.

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Andrzej Kisiel

Interference Spectroscopy Group,

Department of General Physics, Institute of Physics, Jagiellonian University, Kraków, Poland

Some historical remarks

The scientific subject-matter of the Interference Spectroscopy Group (ISG) originated with the high resolution spectroscopy investigations of atomic spectral lines structure, which were initiated in the early fifties by F. Leś in the Department of Experimental Physics under the supervision of Prof. H. Niewodniczański. Around 1967, a group of people dealing with the subject formed a separate Department of High Resolution Spectroscopy which — following the suggestions of the Ministry that the names of Departments should not be too specific — was soon renamed and became the Department of General Physics (DGP). After Ass. Prof. F. Leś, the head of the DGP, had left, his duties were performed by Dr. Z. Leś for a few years. In 1973, on mutual agreement, a group of physicists working on optical spectroscopy of semiconductors in the Department of Experimental Physics under the supervision of Ass. Prof. A. Kisiel, joined the DGP, and Ass. Prof. A. Kisiel (now Professor) has became the head of the new body. The physicists dealing with the investigations on atomic physics by the methods of the high resolution spectroscopy have formed within the DGP the Interference Spectroscopy Group, supervised by Ass. Prof. Z. Leś.

Scientific activity, results and prospects

From the very beginning, the main subject of scientific research was the experimental investigation of the influence of atomic nuclei on the structure of atomic spectra, carried out by means of the Fabry-Pérot (FP) interferometer as a high resolution spectral instrument. In those days, there were enormous difficulties with getting the ready-made FP plates as well as other optical elements, and that is why the two basic activities had to be undertaken:

i) A technical laboratory for polishing glass and quartz with possibly great accuracy was organized, which has proved very useful not only for the ISG but for the whole Institute, as well.

ii) A vacuum apparatus was constructed to produce metallic and dielectric reflectors for visible and ultraviolet regions of spectrum by thermal evaporation method. This apparatus has been used for the investigations performed by the ISG as well as by other scientists from our Institute and, occasionally, from other centres.

In the course of working on dielectric reflectors two more or less separate research branches have emerged: studies on properties of atomic nuclei by methods of high-resolution optical spectroscopy and thin-film optics.

The ISG is rather small as it consists of three physicists only and one chemist dealing mainly with the preparation of optical coatings. However, there are always some voluntary

co-workers; moreover the ISG is in touch with the Clarendon Laboratory in Oxford, Great Britain. Both projects are supported financially by the Committee of Physics of the Polish Academy of Science.

Studies on the properties of atomic nuclei by the methods of high-resolution optical spectroscopy

There are two main reasons for which the spectral lines of free atoms are split: i) the so-called hyperfine structure (HFS) due to interaction of the dipol magnetic and quadrupole electric moments of the nucleus with its electronic shell, ii) the so-called isotope shift (IS), due to the differences in the parameters of the nuclei of various isotopes of an element, such as their mass (IS mass effects) or charge distribution (IS field-effects). The ISs are, generally speaking, of the same order of magnitude as the HFSs and can lead to very complex patterns. Both nuclear effects are mixed with those due to electrons of atomic shell and that is why the electron eigenfunctions for a measured structure to be interpreted from the viewpoint of nuclear properties must be known. When, however, these properties are known from some other investigations, the HFS and IS results can be used tostudy the details of the electronic structure.

The smallness of most HFSs and ISs requires special spectroscopic techniques for their study. A classical method of high resolution optical spectroscopy has been applied in our laboratory. A hollow cathode with liquid-nitrogen cooling, which has proved to produce quite narrow spectral lines is the light source. Samples of enriched isotopes are used. For many years, the structures of spectral lines were investigated by the Fabry-Pérot etalon crossed with a spectrograph, the interference patterns being recorded on a photographic plate. A very stable and convenient FP interferometer suitable for this task was constructed and its copies are still successfully used in various educational and other laboratories. In the late seventies, we started completing a new experimental set-up for the electronic recording of interference patterns, with photon counting and digital data recording, partially in collaboration with the Clarendon Laboratory in Oxford, after a one-year stay of Dr. R. Kloch in that laboratory. A pressure-scanned FP interferometer was designed and built (paper 2), and proved to be very good. A computer program for numerical handling of the FP interferograms was worked out in order to improve deconvolution of experimental results. The whole system is now at the testing and detail-fitting stage.

The four papers (1, 5, 7, 8) are devoted to IS and HFS studies. The first one deals with the theoretical calculations of the IS mass effects in light elements. The latter three refer to the IF and HFS measurements in the atomic spectrum of zinc and their interpretation. The conclusions concerning the variation in the nuclear charge distribution as a function of neutron number in zinc nuclei have been drawn encountering both the muonic IS results just published then, as well as the results of electron scattering and Coulomb excitation experiments.

Thin-film optics

At the beginning only experimental research on optical properties of thin-film coatings was carried out. Chiefly the so-called quarter-wave reflectors were investigated and produced for the FP interferometers and then also for lasers.

A quarter-wave reflector consists of a number of layers of two dielectrics with high and low indices, superimposed alternatively, the optical thickness of each layer being $\lambda_0/4$ (λ_0 being the chosen wavelength), at the top of the stack there ought to be a layer with a high index. The advantage of such dielectric reflectors, when compared with the metallic ones, is that their absorption is usually negligibly small. They, however, have an essential drawback — they are very selective as their hight reflection is limited to some narrow region around λ_0.

For many optical purposes it is very desirable to have dielectric (i.e., nonabsobring) broadband reflectors, that is the reflection of which is possibly steady in a possibly broad region of spectrum. Since such systems must be composed of quite a large number (usually several tens) of layers of various optical thicknesses, the problem of finding the parameters of their structure, i.e., the refractive indexes and thicknesses of layers, becomes very complicated. That is why before starting the experiments, the problem must be solved theoretically, most often by means of a numerical method. This is also true for many optical dielectric filters. As far as the broadband reflectors are concerned, it appears that the design of high-reflection but still semitransparent systems is even more difficult than that of the entirely reflecting systems. Additional difficulties arise when the dispersion and absorption of the materials are to be taken into account, which proves essential for practical realization, even if the absorption of dielectrics is relatively very small.

Our interest in the numerical design of the dielectric multilayer optical coatings with prescribed spectral characteristics goes back to the middle of the seventies. We started with the synthesis of broadband semitransparent reflectors first without and then with dispersion and absorption. The methods developed by us yield the systems with relatively very good parameters. The four papers (3, 4, 6 and 9) deal with the problem. At present, a method for synthesis of broadband filters is being searched.

There are many problems with getting, in our present equipment, the dielectric and metallic thin films of equal thicknesses over a sufficiently large area, because the coated plates are motionless during the process of evaporation. Some years ago we started building a new apparatus by means of which we hope to get much better results. The construction si already far advanced.

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Zofia Leś