Technological aspects of optical material selection in infrared techniques

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1. Introduction

Optical elements designed for instruments operating in the IR range constitute a separate, big and miscellaneous group. A base for the knowledge on designing of these elements was laid by a long experience in designing optical systems for visible range, gathered since the beginning of 17th century. The design of top-quality projection optical systems takes into consideration some aspects of construction, manufacturing (tolerances) as well as material aspects – including the influence of material properties fluctuation on the performance of optical system (material aberrations). Universality of the optical element production, accompanied by development of a standard technology, enabled to elaborate criteria for assessment manufacturability of optical system designs. These criteria could be used by computer programs as factors determining selection of the final version of an optical system.

The progress in IR optics has created new demands and applications for a wider and wider variety of optical materials, also for those unknown before, featuring more and more miscellaneous properties. It gave stimuli for elaboration of new techniques of their manufacturing and processing, and due to some additional feedback it resulted in improvement of conventional optics technology. It has been particularly intensified by development of semiconductor material technology, photolithography or surface processing of non-spherical metallic elements for high-power lasers. Optical materials for the IR range are well reported (Refs. [1] to [6]), so are their manufacturing [7] and processing (Refs. [8] to [11]).

In this paper, major relations between optical material properties and technological steps, such as semi-product forming, processing and assembly of optical elements, are presented. Materials for optical devices operating in the IR range are discussed (i.e. for thermovision instruments, locators, high-power lasers, excluding optical fibers, which are a separate group showing specific features – see Refs [12] and [13]).

2. Designing optical systems for the IR range

It is assumed, that the IR ranges of under 3 μm, 3 to 5μm, and 8 to 12 μm are particularly interesting since they correspond to atmospheric transmission windows. The range below 3 μm does not create any difficulties in design of instrumental optics. In this range (especially for $\lambda < 2$ μm) most materials from silicate optical glass group, which are applied for visible-range, may be used. They feature the refraction index of 1.36 up to 2.1 and the dispersion coefficient $\nu_d = 15$ to 100. Also, materials typical for medium-far IR range may be used here.

While discussing details of optical designs for the ranges mentioned above, it may be noticed that, comparing to the visible range, the spectral range is much wider, causing bigger troubles with achromatization of an optical system, due to bigger changes of the refraction index. Also, the variety of materials of different dispersion, needed for achromatic correction, is still small. Therefore, in the cases, when high-quality imaging and high brightness are required (e.g. in the case of objectives of interferometric systems), mirrors are used instead of lenses. The value of the refraction index for IR materials lies within 1.35 to 4.1. High value of refraction index (particularly for semiconductor materials like Ge, Si, GaAs) enables to design systems of high F-number. However, it results in high Fresnel reflection losses, leading to decreasing transmission of the optical system. Application of anti-reflection coatings may essentially reduce the losses down to the value of 0.1% (i.e. to the level caused by a scattering and absorption), but only for one, selected wavelength. Obtaining multi-layer achromatic coating for wider spectral range is much more difficult technological problem.

Comparing designing of visible range optical systems and those for the IR range, it can be noticed that difficulties are smaller for longer wavelength. Since diffraction resolution decreases proportionally with the increase of the wavelength, then also manufacturing requirements are becoming lower. This concerns for example the shape of optical surfaces, their alignment and distances between them. For instance, the spherical surface of a lens, which meets the Rayleighs $\lambda/4$ criterion of projection quality, may be manufactured with 20 times lower accuracy for the CO_2 laser than for the visible range. Using a material of a different refraction index slightly modifies wave-front deformation $\Delta E = (n-1)\,\varepsilon$, where ε is a shape distortion of the refractive surface.

Also, a greater wavelength influences on optical surface microgeometry, since amount of light scattered by surface defects decreases inversely proportionally to the square of wavelength. This rule, related to a total light energy, dissipated by a surface featuring the quadratic mean height of surface irregularities, may be presented by $(4\pi\varrho)^2/\lambda^2$. Therefore, it may be assumed, that for a typically polished surface the energy loss due to scattering will be, for instance, 280 times bigger for the CO_2 laser light ($\lambda = 10.6$ μm) than for the He-Ne laser ($\lambda = 0.633$ μm). Actually, surface roughness of IR optical elements does not cause technological problems in location, thermovision or low-power laser systems, even despite different processability of different materials. However, this becomes important for optical elements of laser resonators (e.g resonator mirrors, Brewster windows inside a resonator), high-energy systems or some measurement systems (spectrophotometers, radiometers), where it is required to minimize the noise produced by the scattering of light inside a system. Optical surface roughness also influences the durability of optical elements.

Optical cleaness of the surface, evaluated according to a number and size of point or linear defects, producing diffraction effects which decrease with light wavelength, constitutes additional important requirement on the laser elements mentioned above. Single local surface defects make laser damage threshold lower, even 100 times, while generation of energetic shock also depends on defect shape, its size and on a dielectric constant of a material. Assuming, that defects of size below 0.01 μm are acceptable, the technological problems of surface processing for IR optics are becoming less critical for longer wavelength. However, proper material selection, favourable for obtaining low surface roughness and high finess of laser elements for special purposes, is still very important.

Relatively lower requirements on projection quality of IR optical systems result from using such detectors, for which theoretical resolution of an optical system is much higher than the one limited by detector geometry (point detector, linear detector or CCD matrix).

Relatively high noise level is a trouble, specific for infrared optical equipment. The reason for this is that optical elements and their mountings are getting warm, thus becoming parasitic light sources themselves. In case of short-wave optics, parasitic light was caused only by reflections. Carrying away the heat requires mounting cooling as well as optical element cooling. Therefore, these elements are made of materials enabling carrying away the heat, especially in high-power laser systems.

3. Properties of optical materials and their technological evaluation

3.1. Selection of optical material

Optical system designer starts his design-work with searching materials of the properties which are fundamental for the function to be realized by a designed system. The two features, transmittance and the refraction index in a selected spectral range, enable to design an optical system, which generally meets the requirements regarding image geometry and projection quality. The possibility of finding alternative solutions, due to the flexibility of calculating programs, opens the gateway for variational selections of different materials realizing particular design pre-requirements, like for example the selection of well-matched material pairs forming achromatic doublets. Then, while making a decision, other properties are taken into consideration, which are of importance for the production, testing and operation of the equipment. Besides, costs are also included into this consideration.

So, material selection, made by a designer, is a two-phase process:

- selection of one material from among a group of materials featuring similar optical properties
- formulating and selection of requirements specific for a selected material.

In the first phase, the following optical properties are considered: n_λ, spectral characteristics and dependencies of these parameters on wavelength, temperature, time and ambient conditions, which, in turn, will influence the optical characteristics of a created system. In the second phase - deviations of real characteristics from catalogue values and changes of homogeneity of these properties in a semi-product are considered.

Non-optical properties are the second group of properties taken into account by a designer, while considering conditions of processing, assembly, aligning, testing and operation of the optical equipment. These properties are:

- hardness and grindability – for the case of optical elements, which are exposed to direct mechanical influence during operation; for example, front surfaces of an optical system, windows, screening calpacks,
- thermal properties: thermal expansion, conductivity, specific heat; here, design manufacturability is based not only on the selection of a certain material for a single element but also on the capability of selection of materials, featuring counter-properties thus mutually compensating the negative thermal effects.
- good matching of substrate material with thin-layer coating materials, defined as high durability of the coatings thanks to good adhesion – free of stress, good correlation between chemical properties of a substrate and a coating.
- easiness of joining optical elements together with each other or in mechanical holders.

Less experienced designer would consider factors influencing proper operation of a ready system, ensuring durability, stability of parameters, optimum functionality – as the most important, while those left by this designer as less important, i.e. processing and mounting features of the optical materials to be applied, are the features really determining the manufacturability level of the design.

The third group consist of economical and commercial factors, such as accessibility, commercial sizes of semi-products, price, and delivery terms.

3.2. Dispersion characteristics of optical material

Selection of material of a high or low refraction index results in Fresnel reflection losses at the interface between two media. The losses are described by equation:

$$R = (n_2 - n_1)^2/(n_2 + n_1)^2.$$

For a germanium element ($n = 4.1$) working in the air, for instance, this will give the losses $R = 0.37$, while for a fused silica ($n = 1.44$), at the same wavelength, the losses are $R = 0.03$. Thus, such a decision may result in the necessity of applying a brightening coating, sometimes even a multilayer coating, in a wide spectral range. Gluing, which radically improves this effect in optical instruments of the visible range, brings no effect in this case, since there are no glues of comparably high refraction index. This phenomenon also causes stronger gleams generated by inner reflections inside an optical element, thus increasing the noise level. In neodymium glass plates of the NOVA laser, for instance, this problem was solved by applying a special polymer coating for margin optical surfaces, which worked as an immersion absorber of the parasitic light.

Technological advantages gained by applying high-refraction index materials result from the fact, that the lens made of this material may have bigger radius of curvature than for the case of low refraction index. Therefore, it is easier to make lens of high F-number, so the energy density for laser light propagation is getting lower. Lenses are thinner what makes cooling easier, which is particularly important for the case of increasing heat absorption in germanium or gallium arsenide, for instance. Sizes of the semi-product as well as material consumption are relatively smaller. Bigger radius of curvature increases the efficiency of processing, since, for a group processing of spherical surfaces more lenses may be processed simultaneously, fixed in a single holder.

The difference in refraction indices ($n_o - n_e$) is used as the operation principle of phase plates ($\lambda/2$, $\lambda/4$). These plates may be monolithic – of the zero or higher order, or composed of two mutually compensating monocrystallic plates crossed with each other and made of the same material, or, for the case of achromatic plates – made of materials featuring different dispersion, like for example CdS + AgGaSe for $\lambda = 9$ to 11 μm. The final optical effect in form of a difference in optical paths equal $\lambda/2$ or $\lambda/4$, is obtained by combining both plates first and then by polishing one of them, until the expected effect is reached. In respect of technological process, the material of the polished element – apart from a good processability, should be characterized by a small birefringence in order to secure a high sensitivity of the operation.

New technological problems have to be coped with when processing materials featuring gradient refraction index (GRIN) optics due to the necessity of maintaining steady direction of this gradient with respect to the base surfaces.

3.3. Transmittance spectral characteristics

The following information has to be taken into account:

- value of the transmittance for a fixed wavelength, as an acceptable minimum value of the transmittance coefficient or as attenuation,
- position of the edge limiting the spectral transmittance area for a given transmittance level,
- modification of spectral characteristics of the transmittance under the influence of environmental factors,

– ability to correct the transmissive properties of a material by covering it with a thin-layer coatings. In respect of manufacturability, the choice of a substrate material will determine the level of technological and design complexity of these layers, as well as the quality and durability of their adhesion to the substrate,

– emissivity – this parameter has a particular importance in IR systems in respect of the noise reduction.

An important requirement, which is essential for manufacturability of a design, is that an optical material is highly transmissive in the visible range. This enables for utilization of many universal measurement and control instruments, which are applied in production of conventional optical equipment, e.g. instruments for measuring optical homogeneity of the material or misalignment of lenses. This may be helpful in assembling, since positioning of optical elements may be determined, for example by the He-Ne laser light.

Spectral characteristics of the transmittance in case of semiconductors is more complex. It may be presented using germanium as the example, which, according to a doping may be *n*-type or *p*-type and of varying resistance. This causes varying absorption, increasing with the temperature, thus leading even to optical system deformation. In general, for a given temperature, the absorption coefficient is proportional to square wavelength, since it is related to carrier excitation up to the higher energy levels. For resistivities below 50 Ωcm, the absorption coefficient is different for the *n*-type and for the *p*-type, however, it is smaller for the *n*-type. For the *p*-type the absorption increases as the resistivity decreases – with the increase of the hole concentration in the valence band. For the *n*-type germanium, there is a minimum of absorption (having justification in theory), which, for example, for $\lambda = 10.6\ \mu m$ corresponds to the resistivity equal of 9 Ωcm (at the temperature 300 K). A further decrease of the resistance is accompanied by a fast increase of absorption, though it will not reach the values typical for the *p*-type germanium.

For a certain type of material, there is a temperature value from which a rapid, exponential growth of absorption is observed (so called thermal escape). In germanium this value is greater than 70°C though the process starts even earlier, at temperatures of 50°C. For *n*-type germanium resistivity of 5 to 40 Ωcm is recommended, which corresponds to the absorption coefficient $0.02\ cm^{-1}$. The elements, which are not exposed to heating and which operate in a temperature much lower than the critical value (i.e. below 70–100°C, depending on the catalogue), may be made of materials of such resistivity, which is characterized by lower thermal escape threshold, but for which the absorption loss is lower.

The absorption increase in the germanium optical element may also be a result of surface processing method used in production. To a big extend, it depends on the presence of germanium oxides, hydrocarbons or adsorbed water, and it varies from 0.05 to 0.7%.

3.4. Semi-product

The selection of a semi-product creates serious dilemmas. One of them is the inner structure of a material – whether it is glass, devitrificate, mono- or polycrystal, or optical ceramics. Technological aspects of such a selection may be considered in the case, when the same chemical compounds exist in different forms.

In the group of optical materials for the IR optics, glasses constitute a sizable part, represented particularly well by oxide optical glasses, applied in close infra-red region and being based on silica (SiO_2). Apart of them, halogen and chalcogen glasses make a meaningful group. Glasses, as a construction material, have many technological advantages: they are isotropic in every respect, with quite easily obtainable homogeneity. The glasses may be easily formed (by casting) into shapes of finished elements, what is particularly useful when making elements of big-sizes (e.g. 1 m long neodymium glass rods). Optical properties of the glass may be relatively easy modified by altering chemical composition or technological process.

Applying a monocrystals is usually justified by optical reasons, like in the case of materials, in which as a result of interaction of polarized light the following effects are expected: electro-, magneto-, piezo-, acousto-optical effects, or nonlinear effects (e.g. harmonic generation). In such cases the orientation of optical axis is determined by a designer. It remains for a process engineer to obtain the assumed requirements. However, he hopes that a tolerance of the axis orientation in relation to base surfaces of the optical element is reasonable and justified, because the difficulties associated with the orientation setting are increasing dramatically with the increase of accuracy. For example, setting the ADP crystal orientation with accuracy of 6 angle minutes may be still accomplished by optical methods using a konoscope, but higher accuracy requires X-ray goniometrical methods. Sometimes, it is enough to use natural planes forming crystal shape, or cracking planes. However, splitting a crystal block is dangerous because of inducing undesirable cracks, manifesting themselves in further processing steps, sometimes in the final phase of the process. This, for example, often happens to a block of NaCl monocrystal, crystalizing into a cubic structure, which can be easily divided by a stroke, but later it begins cracking, starting from the edges, because of vibrations (induced by mechanical processing) or because of even quite insignificant thermal stresses. Stresses induced by mounting also propagate easily and deeply.

The method the crystal was obtained, is also quite important. The weakest stresses are induced when a crystal is pulled very slowly from a steady temperature solution. However, temperature gradients occurring in the course of liquid phase solidification are high, especially in the Verneuil's method, formerly used (crystal is grown in flames of the hydroxide burner and the temperature drops by 1000°C over a distance of 5 cm). These gradients create very high thermal stresses. For example, a ruby crystal obtained without additional de-stressing process cracks on the first touch of a diamond saw. Therefore, an experienced cutter always started ruby pearl processing with a hammer stroke, causing its cracking along the plane of the biggest stresses. Distribution of the stresses may be nonuniform; external layers are under tension and internal layers - under compression, what can be observed with the use of an interferometer. It may be expected, that material micro-homogeneity, corresponding to dislocation distribution, will vary, according to the method applied for crystal forming and it will be much better when applying moving-phase method. Still, applying a chemical vapour deposition (CVD) method enables better chemical composition control while crystal growth, as it takes place in manufacturing of quartz preforms for optical fiber production.

Technology of polycrystallic materials seems much easier than making monocrystals. Polycrystals may be obtained using crystal growth processes, glass devitrification or powder sintering and pressing, which is the method for manufacturing of ceramic materials for optics like IRTRAN. They feature good, isotrophic mechanical properties, important for non-destructive processing, and also of thermal, chemical and optical properties. Sintering and pressing may be performed in the conditions, which guarantee a proper chemical composition. Also, keeping temperature within certain range can minimize thermal stresses and, as a consequence, birefringence. Particularly advantageous is the fact that there is the possibility to form the semi-products so as to obtain the shape and sizes of optical elements with a slight extra margin (an oversize) for finishing the optically active surfaces. However, it is also possible to perform the pressing process in such a way, that such a surface would be smooth enough, thus requiring no polishing. High temperature and polished surface of a tool enable to produce, using the above method, big CaF_2 windows or lenses. Similarly, KCl has been processed: between two polished plates of fused silica or pyrex, in the temperature 200 to 250°C, under the pressure 30 MN/cm², in helium ambient. The obtained surface roughness (5 to 8 nm RMS value) and backscattering for $\lambda = 10.6\ \mu m$ ($1.8 \cdot 10^{-5}$) was considered to be satisfactory for IR optics of medium quality. Yet, there are also some disadvantages of ceramic materials in comparison with monocrystal: higher Rayleighs scattering in a short-wave region or lower chemical durability due to the edge corrosion effect – at the crystal grains edges.

While selecting a material from a catalogue, a designer usually does not know, what technologies were applied to manufacture the material, and, consequently, what might be the resultant differences.

3.5. Hardness

Physical properties quite obviously correspond to technological properties of a material. As a reference, optical glass can be given, for which technological process is stable and widely used. Materials harder than glass (for which the Mohs' hardness number is 5 to 6, while for fused silica it is 7), such as silicon (hardness 7) or spinel (hardness 8) create no particular processing problems, due to their hardness. Also processing of corundum-like materials (ruby, sapphire – hardness 9) is relatively simple, thanks to the application of sintered carbides tools, though rather poorly efficient, especially in the case of fine polishing operation.

High hardness of a material makes it more resistant to casual surface scratch, which might happen during such auxiliary operations as mounting in the processing holders or final assembly. Materials softer than the optical glass, such as ZnSe, ZnS, CaF_2, As_2S_3, CdS, and particularly crystals like CdTe, BaF_2, KRS-5, AgCl, NaCl, KCl, KBr, KJ, CsBr require special operator's treatment and particular attention to avoid the danger of local scratching of the optically active area. Therefore, geometrical measurements are impeded by the necessity of using non-touch sensors (pneumatic or optical). While checking the surface shape during polishing, instead of interference glass gauge, it becomes obligatory to use interferometer.

For polishing, most often soft textile is used, or wax composition on a polishing tool formed by a special glass pattern. A danger of scratching the surface during the polishing requires special polishing slurry of uniform graininess as well as keeping high room cleanness, to avoid casual appearance of a coarse abrasive grain. The polished surface is covered with a protecting varnish, therefore, while polishing the second surface of the optical element – the base cannot be determined precisely. Thus, the linear dimensions and angles of the optical elements made of soft materials should have rather wide tolerances. For the same reasons, for soft materials mounting bases are treated differently than in the case of harder materials, for which lens mounting in its holders is usually designed to be coaxial with the reference to lens edge – polished during aligning operation. This operation is not performed for soft materials (especially those water-soluble), so proper lens positioning has to be achieved by extended mounting adjusting regulators.

3.6. Density

Searching for low density materials among refractive ones does not constitute technological problems. Much more interesting is the problem of mirror weight minimization, because of the requirements imposed by satellite laboratories designers or because of the gravity effect causing deformation of optical surfaces in large telescope mirrors. For these reasons materials of low density are demanded, such as beryllium, aluminium, silicon carbide, silicon, fused silica, ZERODUR and also sintered porous materials made of beryllium powder or Al/SiC composite foam materials, which are light and stiff.

Limitations, caused by the impossibility of obtaining sufficiently smooth surface of a heterogeneous material by polishing have been overcome by introducing hybrid mirrors. The optically active surface of the hybrid mirror is impressed with a glass pattern in a layer of a hardenable material covering the mirror substrate. Using such a material is cheaper than polishing metal surface, so the hybrid mirrors are becoming more frequently applied, when a material cannot be easily polished (like soft copper, for instance) or when its mechanical processing is expensive (like in the case of aspherical surfaces). Together with making a replica of a mirror surface shape, a mirror layer and a protecting dielectric layer may be transferred onto the surface. This technique may be used for laser systems, in which power density does not exceed 500 W/cm² in a continuous mode or 8 MW/cm² in a pulse mode.

The example of high power CO_2 laser is useful to discuss other aspects of material selection. For the last decade, together with the increase of laser power, the number of mirror substrate materials has decreased due to the selection according to quality; materials of worse properties or those more expensive have been eliminated. Such materials as molybdenium and copper, covered with the Au-Ni layer, are still applied because of their unique thermal properties. However, silicon is becoming more and more popular material for mirror substrates, successfully substituting copper, though some limitations are imposed by its thermal properties.

3.7. Thermal properties

This is an important material selection criterion for high-energy systems. The mirror substrate must act as heat absorber, protecting the mirror against deformation caused by the heat provided by a laser beam. Small thermal expansion coefficient will ensure small surface deformations. Heat conductivity of copper is 2.5 times higher than that of silicon, but this advantage is pulled down by 6.5 times bigger thermal expansion coefficient, therefore, shape stability of a silicon mirror is better.

Pure, polycrystallic and fine-grained oxide free copper, used as a mirror substrate, is soft and ductile, thus it is not easy for polishing using the conventional techniques (grinding, lapping and polishing). For that reason, diamond turning is a recommended and applied processing method, requiring special precise machines. In this respect, silicon present itself advantageously for spherical surfaces. It is cheaper and easier to be polished. On the other hand, copper is more convenient to introduce channel cooling system, because of its good machinability. And its surfaces seldom become destroyed by a thermal shock caused by a laser beam, thanks to its good heat conductivity.

A possible active surface deformation may also be caused by improper assembly. Such physical properties as the Young modulus and the Poisson modulus indicate the recommended thickness-to-diameter ratio and the holding force to be applied when mounting a mirror in a system.

The thermal properties mentioned above, have the effect on shape durability, thermal deformation and also on optical properties, i.e. transmittance (discussed before while presenting germanium) and refraction. Under the influence of a laser beam, a material is heated due to the internal absorption and surface layer absorption. A change of the optical path, caused by a change in element length and the refraction index, also depends on such material properties as a thermal expansion coefficient, Poisson number, index of refraction, density and dn/dT – a growth of the refraction index with temperature. This increment may be positive or negative for a particular material, thus providing opportunities for mutual compensation of these changes and also for compensation of other thermal effects; on optical system power, on variations of optical system thickness or radius curvature deformation due to thermal surface deformation.

Low resistance to rapid thermal changes is a really troublesome thermal feature of such materials as NaCl, KCl, KBr, ADP and, to a smaller extend, $CaCO_3$, BaF_2, $LiJO_3$. Mounting in processing holders with the use of thermoplastic glue requires special care, since temperature changes, while heating or cooling, should remain very low (not exceeding 10°C for a period of 15 minutes). Also, optical coating deposition process is rather time-consuming, because, in order to avoid rapid cooling, a vacuum chamber should not be opened, but should be left for total self-cooling. For the same reason, such products as NaCl plates, for instance, must not be put directly on a metal surface, because even slight difference in temperature, at high heat conductivity of a metal, induces a difference in temperature inside a plate, which is sufficient to cause its cracking. Needless to say about the heating effects caused by manual polishing, when, for instance, the amount of polishing slurry is not sufficient.

As a rule, semi-product annealing should be carried out before processing, in order to get rid of stresses.

3.8. Chemical properties

They directly influence a technological process. Many crystals pulled of water solutions are vulnerable to humid ambient. Therefore, chemical properties require applying of appropriate fluids for rinsing of optical elements, inactive to these elements, like for example, freon. For drying, a stream of warm dry air or nitrogen should be used. Also, the surfaces should be well protected between technological processes and the elements should be well stored.

Such materials as LiF, BaF_2, CdF may be easily spotted, similarly like some lanthanum optical glasses, but real problems are with such materials as NaJ, KJ, CsBr which feature solubility beyond 100 g in 100 g of water. So, mechanical-chemical polishing may be carried out very easily, but it is difficult to finish the polishing still having the surface clean. The surfaces are protected with water-proof varnishes (high-molecular polymer coatings are not good insulators). Optical elements should better be stored in special vessels, so as to keep their temperature a bit higher than the ambient temperature, thus avoiding humidity condensation. One can imagine difficulties in using these elements, despite the commonly applied thin-layer optical coatings as a protection and at the same time as interference layers. In high-power lasers, like CO_2, usually such coatings are not used due to their smaller resistance to laser beam, but the exposed surface is kept in a dry ambient. For example, in Los Alamos Scientific Laboratory the atmosphere is naturally of a very low humidity. Possible surface corrosion may be neglected in view of the rule that laser light scattering is reversely proportional to the square wavelength. Water absorption by a surface layer may also be minimized by heating the surface, before the real experiment, with a radiation of a lower energy.

A separate problem is the processing of toxic materials, containing arsenium and thorium compounds, or among metals, beryllium, which is toxic only as a powder breathed in. In such a case, technological staff must be protected against admission of these compounds to an alimentary system, or exceptionally, to a respiratory system. This is achieved by carrying out wet processing, in isolated chambers.

A specific difficulty is caused by photo-chromatic materials, which change their transmittance when exposed to the light. AgCl is a particular case: it turns purple, so its processing is performed in a darkened room, by red light only.

3.9. Processability

This criterion is hard to define, though the factors influencing the scale of difficulties and efficiency of material processing are very carefully studied, when selecting of an optical material. Processability evaluation takes into consideration a certain technological base being at disposal of a potential producer. Also, this evaluation takes time and costs of the processing into account.

The main goal is to obtain an optically active element of a shape, which is characterized by two attributes: macro- and microgeometry. The comparison of the obtained shape with a shape required by a designer, the roughness of the surface, its optical cleaness (scratches or point defects), the thickness and absorption coefficient of the surface layer, belong to the group of quantitative requirements. Basically, there are four methods to meet these requirements: 1) by forming a material in such a way, that mechanical processing of the optical surface is not necessary (pressing, casting, injection moulding), 2) by polishing with a stiff lining (textile, polyurethane) or plastic lining (mallet pitch, synthetic plastics), 3) cutting machining with a single diamond grain and 4) forming of a desired shape in a plastic layer, deposited on an optical element, using a shape pattern, often with simultaneous introduction of thin-layer coatings.

Material selection is connected with a type of processing and the way it is performed. For example, the best roughness is obtained for such materials as a silicon glass (RMS value less than 0.5 nm); stable surface shape - in materials of minimum thermal expansion coefficient, i.e. ZERODUR type devitrificates ($\alpha = 0.05 \cdot 10^{-6}/°C$ for $T = 20$ to 300°C). Sometimes, the polishing process is an uphill task, when, like in ZnSe, in the course of polishing microscopic surface deviations appear ("orange skin"), which are the effect of anisotropy of mechanical and chemical properties of grains, of which a polycrystal or ceramic material is made. There are materials in which the polishing process should be stopped in the right moment, otherwise, further polishing will result in surface quality degradation and small scratches will become apparent, which are sub-surface microcracks, caused by faulty grinding preparation before polishing. This is called a skating rink effect. Similarly, for different materials the polishing time influences the surface layer thickness in a different way, and for the BK-7 optical glass this layer is the thinnest after polishing for 30 minutes, and only then. Also, crystallographic orientation of a material may or may not improve the polishing – this can be observed in the case of CaCO monocrystals.

Now, more often a precise diamond turning substitutes polishing. It is mostly desired in case of big aspherical surfaces, but it is required that a turning machine offers the precision of 0.1 μm. This processing may be applied not only for metals, but also for other well mashinable materials like CaF_2 or NaCl or even for a modified optical glass. One of the most significant advantage of this processing is the chemical purity of a surface layer, contrary to the conventional polishing, which induces impurities originating from a polishing slurry. Diamond machining of a surface also results in its higher resistance to laser light, in spite of its relatively higher roughness introduced by a diamond cutter.

Other properties, mechanical, thermal and chemical, having their technological consequences, were discussed earlier.

3.10. Resistance to laser light

Relations between material properties and the resistance to high-energy laser light are the area of comprehensive studies and are frequently reported (e.g. in Refs. [1] and [14]). They are also presented during annual conferences. Proceedings from such meetings are the source of information of fundamental importance [15]. The refraction index of a material, its dispersion, nonlinear effects, internal and surface absorption, scattering, emmissivity, internal structure, purity and other physical and chemical properties, together with miscellaneous radiation characteristics, such as wavelength, exposition time and repetition rate, polarization, energy and spatial distribution - build up a collection of very interesting relations, which in turn, indicate directions for technology optimization of newer and newer materials. Relations between processing techniques, properties of a surface, thus obtained, and the effect produced by a laser beam on such a surface [16] are directly corresponding to the above issues. However, these problems constitute separate subject.

The above considerations may be synthesized as follows: in designing, technological aspects cannot be neglected. This thesis may seem to be a cliche, but only to those who do not need to stick to this rule.

4. Summary

Designing optical elements and systems for an infrared range (wavelength within 3 to 5 and 8 to 12 μm) is rather specific due to relatively wide spectral band, comparing to a visible range, due to the possibility of applying materials of various refraction indices and energetic noises. With the increasing wavelength, quality requirements concerning projection, macro- and microgeometry of elements and perfectness of optical assembly are becoming less critical.

Particular physical and chemical properties of optical materials correspond to technological properties, which have to be taken into account by an experienced designer. A high refraction index helps to minimize lens thickness, thus improving its cooling and processing efficiency, but it results in higher energy

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loss. A selection of semi-product from among materials of different structure, such as glasses, monocrystals, polycrystals and optical ceramics, may be beneficial for technological processes, especially for the effectiveness of surface processing. Low hardness, dissolubility, low resistance to temperature changes are the reasons for processing method differentiation. From among these methods, diamond machining offers a number of advantages, as well as plastic replication of a pattern surface. Other specific technological aspects are closely related with high requirements concerning the resistance to high-energy laser light.

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