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MATERIALS AND METHODS FOR FLAT OPTICAL ELEMENTS

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Abstract—Consideration is given to the materials and processes suitable for the manufacturing of focusers, i.e. flat elements capable of focusing monochromatic radiation into an arbitrary line with specified intensity distribution. Methods are described for manufacturing optical elements with both surface and phase reliefs due to modulation of refractive index. Manufacturing of focusers by means of photolithography of selective etching of bichromized element, or of focusers with phase relief on layers of glass-like semiconductors are described.

Focusers—optical elements with predetermined fixed focusing properties—are in fact phase zone plates, wherein the height of the phase relief varies continuously at the boundary of each zone from 0 to 2π. Focuser production is therefore equivalent to the preparation of a zone plate with a specific phase profile. The phase change of a wave passing through two different points of a focuser is given by

$$\Delta\varphi = \frac{2\pi}{\lambda}(h\Delta n + n\Delta h),$$

where Δn and Δh are the corresponding changes in the refractive index and the relief height, respectively.

In normal use of an optical element the phase difference across the zone boundaries is required to be 2π. This can be achieved either by creating the profiled zone plate with a maximal relief height of $\lambda(n-1)$ or $(\lambda/2)\cos\Theta$ corresponding to transmitting or reflecting elements (Θ is the angle at which radiation falls on the element), or by using variable index materials. In the latter case the refractive index change must amount to $\Delta n = \lambda/h$, where h is the layer thickness.

Two conclusions are implied by the foregoing discussion. Firstly, the focuser must be made out of flat plates whose surface relief height is of order λ, or in the form of thin films whose material has variable refractive index (with purely phase relief). Secondly, the modulation depth of surface or phase relief is proportional to the wavelength of the incident radiation. Hence the choice of the material and the technology for optical element manufacture will very much depend on the operating wavelength, and on the specific requirements on the element in each particular case.

The present work attempts to analyse the properties of various materials and of production techniques, with the object of utilizing them in flat focusing element production.

To begin with we consider surface relief elements. These are the ones that are currently the most widely produced. This is due, on the one hand, to a highly developed manufacturing technology, and on the other, to a series of useful properties, allowing their use as reflecting elements in laser technology. They can easily be printed by electroplating techniques.

The simplest method of optical element production is by means of a precision numerically controlled machine. Current diamond styluses are capable of achieving an accuracy of $\lambda/20$ ($\lambda = 10\ \mu$m) in aspheric optical production technology [2]. This type of machine is suitable for the production of zone plates, correction plates and other optical elements with axisymmetric zones above the 10 μm wavelength domain. For shorter wave bands focuser design usually requires, in addition, the production of rather complicated surfaces which do not have a closed form analytic description. In that case the element is manufactured by a two-step process. In the first stage a so-called "amplitude mask" is produced on the photomaterial, wherein the blackening density corresponds to the relief height on the optical element. In the second stage the light sensitive material is exposed through the mask. Depending on the irradiation dose, further chemical processing results in a corresponding change of the layer width, yielding thereby a zone plate with the desired profile.

The medium for this type of material is primarily the so-called bichromatic gelatine (BCG), on which focusers in the IR domain ($\lambda = 10.6\ \mu$m) were produced [3]. The quality of the gelatine is responsible, above all, for the simplicity of production of optical elements of sufficiently high quality (the energy effectivity approaches 80%). Such results were obtained on BCG film processed jointly with the Kiev branch of the All Union Institute of Polygraphy. The gelatine film's draw-back is its low resolving power, so that one cannot produce on it an optical element whose zone dimension is smaller than 150–200 μm, which restricts its use mainly to the IR-domain.

Photolithographic methods look extremely promising for manufacturing high quality elements in the IR and visible range. Focusers for $\lambda = 10.6\ \mu$m with an energy effectivity of around 90% were produced by multistep etching of glass via methods developed in [4]. Unfortunately, special equipment is required for the implementation of photolithographic technology: picture developing apparatus, kits for reducing and matching photomoulds, and precision techniques for chemical or ionic etching. On the other hand, mass production will reduce the cost considerably, as has happened in microelectronic technology. Elements might also be reproduced on inexpensive and accessible materials. Visible domain ($\lambda = 0.63\ \mu$m) doubly-graded focusers with an effectivity of 40% have been produced by the lithographic process [6]. If the important feature is high resolving power rather than the effectivity, photolithography gives the best results, since it is capable of producing zones whose dimensions are a few microns.

The most promising materials for producing optical elements in the visible range may well be the chalcogenide semiconductor glasses (CSG) and the CSG-metal systems [8]. In both cases the rate of diffusion of the CSG film changes according to the amount of absorbed light. The resolving power attainable in the process is reasonably high $l(\approx 1000$ line/mm$)l$, while the etching depths 0.5–1 μm are entirely adequate for visible-range elements.

Among materials that are suitable for making surface relief elements are photoresists, especially the negative form which has a linear section in its characteristic curve, although a thorough experimental study is required to evaluate its full potential.

The attraction of variable index materials is that their surface relief need not be specified strictly, which means that surface quality requirements can be relaxed. They are thus less sensitive to surface damage, contamination, etc., in the course of their use. Among these materials one should first of all include the chalcogenide semiconducting glasses already referred to, in which the absorption band is displaced and the refractive index is shifted under the influence of actinic radiation. The shift is of order 0.2–0.3, so that a film of thickness 3–5 μm will suffice to obtain a phase modulation of 2π [9]. Fairly high quality zone lenses and prisms have been produced by this method [9]. In several cases it was possible to reverse the phase relief recording. The present authors have produced visible-range elements on CSG films which were comparable in quality to photolithographically created elements, but the CGS-based elements had much lower effectivity. This is presumably due to the large reflection coefficient of CGS (as $n = 2.6$) and to a certain amount of scattering.

In order to produce purely phase relief flat optical elements one can use widely known techniques for bleaching photomaterials employed in the manufacture of phase holograms [10]. Although these techniques are fairly straightforward, one usually encounters difficulties in obtaining accurate phase matching across zone boundaries [11]. Another factor which interferes with the production of high quality elements is the high noise level.

Another group of materials commanding great interest are photopolymers which change their n in the process of polymerization under the influence of UV radiation. Large diffraction effectivities were obtained in phase holograms made from such materials [12]. They are, as yet, not sensitive enough, but they may find application in the future, thanks to their high transmissivity and stability after polymerization.

There exist other materials with variable n, but it is too early to speak of their practical application, since they are still in the laboratory development stage. Therefore, the currently recognized universal technology is the multigrade photolithographic etching method, although with the tendency towards zone miniaturization the problem of photomould matching becomes acute. In this context one ought to consider alternative technologies, such as selective etching of semiconductors or the use of photopolymers.

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