ТЕХНОЛОГИИ КОМПЬЮТЕРНОЙ ОПТИКИ

COMPUTER CONTROLLING OF WRITING BEAM IN LASER MICROFABRICATION OF DIFFRACTIVE OPTICS

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Abstract

Laser microfabrication of diffractive optics with continuous relief is based on the direct local action of focused laser radiation on the recording material. Control of writing beam parameters (beam power, spot size, waist position) is one of the main tasks in microfabrication using laser writing systems. Method of the control defines the correspondence between the fabricated microrelief of the diffractive optical element and a designed one. Complexity of this task consists in the necessity to take into account a wide range of factors: laser irradiation noises, non-linear characteristic curve of recording material, finiteness of spot size, influence of power modulation and surrounding on beam energy absorption, influence of beam waist position according to recording layer, dependence of characteristic curve of recording material on beam scanning speed, etc. In the present paper we consider a number of methods for computer controlling of writing beam making it possible to compensate or reduce the influence of these factors and improve the quality of DOE microfabrication. The results of experimental application of the developed methods to circular laser writing systems are discussed.

KEY WORDS – diffractive optics, microfabrication, direct laser writing, circular laser writing system.

Introduction

Future development of optics is mainly concerned with broad application of microoptics and diffractive optical elements (DOE), which modulates the initial wavefront by the local variation of optical or geometrical thickness of the material [1]. DOE and microoptics applications in different areas of optoelectronics, laser technologies are permanently extended. The new elements performing complicated geometrical and wave transformations allow one to design and manufacture optical and optoelectronics systems, which are impossible to realize using classical refractive components. However, microoptics and high-efficiency DOEs should have continuous or multi-level microrelief. Fabrication of such 3D microstructures with high accuracy is a serious problem. A number of different techniques are developed for this purpose [2], [3]. Laser microfabrication using scanning focused laser beam allows one to use different light-sensitive materials for generating 3D microrelief or to write gray-scale masks, which are used to create a required multi-level exposure distribution in the photoresist layer at contact printing or projection lithography.

The scanned focused laser beam can locally modify physical and chemical properties of the light-sensitive material with high reproducibility and accuracy combined with high spatial resolution comparable with e-beam writing. Therefore accurate and flexible control of the writing beam parameters (beam power, spot size, waist position) is one of the main tasks in design of laser writing systems. Complexity of this task consists in the necessity to take into account a wide range of factors influencing the formation of the final microrelief: laser irradiation noises, non-linear characteristic curve of the recording material, finite spot size, influence of power modulation and surrounding on beam energy absorption, influence of beam waist position according to recording layer, etc. Besides, the type of scanning system considerably affects the requirements for controlling the writing laser beam because the exposure dose depends on the beam scanning speed. There are two basic groups of scanning writers: circular and x-y systems. The main distinctions of these two groups are the following:

- final data format of the given microstructure is represented in different systems of coordinates;
- scanning speed changes in a wide range in the circular systems, but remains constant in the x-y writers.

Despite these distinctions they have common features. The scanning of the writing beam is made along a certain type of trajectories – circle or spiral for circular system, and lines – for x-y systems. Looking at the behavior of the beam on a local area, where the curvature of circular trajectories is not essential, it is obvious that the writing systems do not differ locally. Thus, continuous movement of a laser beam on one coordinate and overlapping of the adjacent written tracks on another coordinate create the image. Therefore it is possible to apply similar technological methods and writing algorithms to both types of writing systems. Experimental data described in this paper was obtained on a circular laser writing system developed in IA&E SB RAS (Novosibirsk) [4].

Writing technologies

Writing technologies and specific requirement on the diffraction efficiency and stray light define tolerances for the laser beam parameters and a method of beam power modulation. Thus, it is necessary to describe typical writing technologies before considering methods for computer controlling of the writing beam.

Direct writing on photoresist

Technology of direct laser writing of multi-level phase DOEs on photoresist started to develop in the early 90s [5]. Early in the development of diffractive optics solitary specimens of DOEs were required for scientific experiments. In this case direct laser writing with the following "dry" etching of the substrate material (if required) ensures the best cost efficiency at high performance. Then this technology was adopted for DOE origination for electroplating and the following mass production of plastic copies. Laser writing systems permit one to write the diffractive structure by direct exposure of a 1-5 μm photoresist layer to the focused laser radiation of 360-460 nm wavelength. Liquid development of the photoresist is carried out by the conventional technology in developers on the base of NaOH or KOH. Exemplary dependence of the profile depth on the laser beam (1 μm) power is shown in Figure 2. To work in the practically linear part of the characteristic curve of photoresist (a part over 1.5 mW in Fig. 2) we used UV preexposure. A mask aligner provides the necessary uniform intensity distribution. The preexposure also permits one to reduce approximately by half the influence of laser beam power fluctuations and beam scanning errors onto the relief depth.

Application of direct laser writing on photoresist for CLWS has considerable specificity because of the necessity to change the laser beam power proportionally to the radial coordinate. Fabrication of large DOEs requires to control laser beam power in a wide dynamic range (>1:10000) with high accuracy.

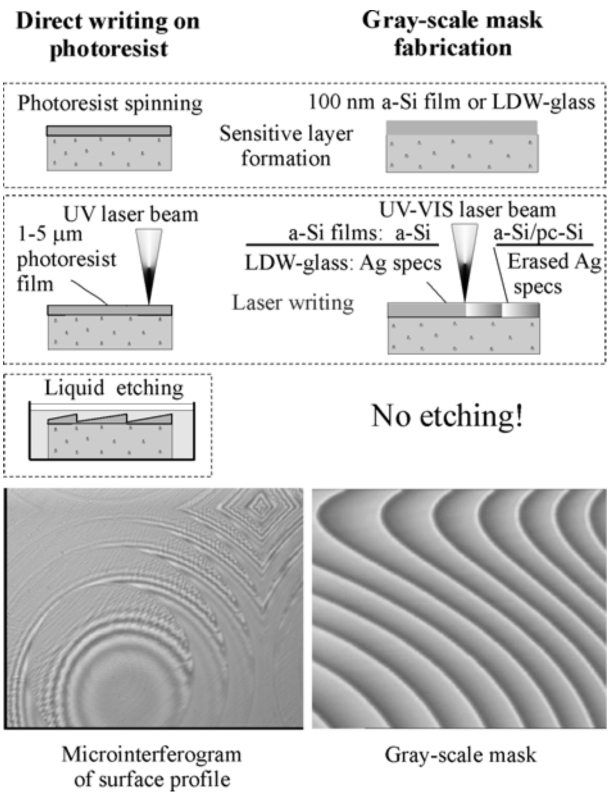


Fig. 1. Direct laser writing technologies

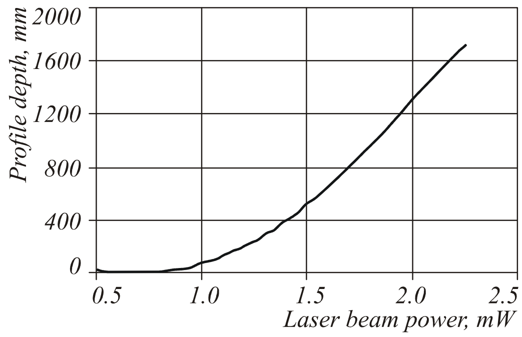


Fig. 2. Profile depth as a function of laser beam power for SC1827 photoresist without preexposure. Scanning speed – 630 mm/sec

This task was solved by using the hardware and algorithm described below. They permit the use of CLWS for manufacturing both axial-symmetric and arbitrary DOEs with high diffraction efficiency. As an example, the lower part of Fig. 1a shows the microinterferogram of a diffractive lens from the microlens array.

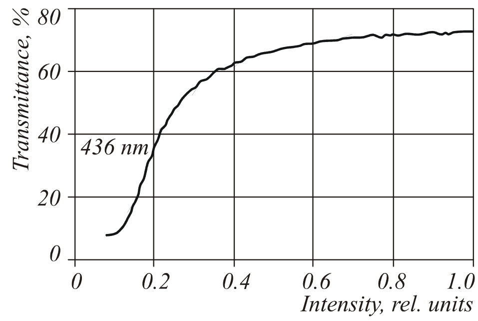


Fig. 3. Exemplary characteristic curve (transmittance as a function of beam intensity) for LDW-glass type I

Gray-scale mask fabrication

In the last years the application of gray-scale masks (GSM) for diffractive optics manufacturing attracts attention because of cost-effective possibility to produce a lot of diffractive or microoptical elements on hard and heat-resistant thermally stable substrates. Single-step fabrication of high-efficiency DOEs can be realized by illuminating the photoresist through the GSM having transmittance depending on exposure dose distribution required. Gray-scale masks can be written directly on LDW-glass [6] (material for Laser Direct Write from CANYON MATERIALS, Inc) or amorphous silicon films (a-Si) without any liquid development process (Fig. 1b). The reduction of optical absorption under heating by laser irradiation is observed in both these materials. The effect in a-Si films is caused by the thermo-induced crystallization. The maximum contrast (the ratio of the transmission of irradiated a-Si film to that of the non-irradiated one) depends on the laser beam power and the scanning speed. The contrast values of 10 have been obtained at the wavelength of 436 nm for 100 nm rf-sputtered films, respectively. It is experimentally shown that this technology allows generating binary and gray-scale microimages with high spatial resolution [7].

LDW-glass blanks have a chemically treated surface layer that contains a large number density of coloring specks of silver. Thickness of the colored layer can be varied from 1 up to 3 μm. The colored layer is at a 0.5 μm distance from the glass surface. The presence of the colored layer inside glass pattern prevents damage of the masking layer at contact printing. Transmission T_o of the unexposed glass surface layer can be made from 10 to 0.1%, respectively, at 436 nm wavelength used in photolithography. The focused laser beam can erase these coloring specks by heating. The optical density of LDW-glass mask decreases with increasing laser exposure energy density. Minimum feature size of microelements with specified gray level is 0.6–0.8 μm at writing beam diameter of 1 micron. Changes in optical characteristics of surface-modified LDW-glasses are observed under the action of focused laser beam with intensity 10^5-10^7 W/cm^2 at exposing time between 10^{-4} and 10^{-7} seconds. Reproducible values of transmittance in the range from $1.5 \cdot T_o$ to 75% were obtained experimentally (Fig. 2). In contrast to a-Si films, LDW-glass has the following advantages: higher transmittance at actinic wavelength of photoresist, long term durability of gray-scale image fabricated, uniformity and reproducibility of optical properties. Photoelectric inspection is used in writing process to get an accurate transmittance curve in diffractive zones of the mask.

Circular laser writing system

To fabricate diffractive optics in different light-sensitive materials the circular laser writing system (CLWS) was developed at IA&E SB RAS [1,14]. It is a highly universal tool for the fabrication of optical elements such as computer-generated holograms, diffractive lenses, microlens arrays, gratings, optical scales, etc. The simplified diagram of CLWS is shown in Fig. 4. The system can be subdivided into five main units: rotation unit (motorized air-bearing spindle with rotary encoder, rotation controller), the radial positioning unit (motorized air-bearing stage, laser interferometer and motion controller), the writing power control unit (Laser power control, modulation control, two acoustooptic modulators AOM1 and AOM2), and the optical writing head (focusing lens, autofocus sensor, reflection photodetector, calibration photodetector, electromagnetic deflector, electromagnetic shutter, writing head controller). All optomechanical units are mounted on a granite base with vibration isolators. The substrate for patterning is fixed on faceplate of a precision air-bearing spindle. The high accuracy rotary encoder is mounted on the spindle axis. The rotary optical encoder forms signals for rotation controller, which stabilizes rotation speed and generates sync pulses for synchronizing laser modulation with turning a substrate. Accuracy of this synchronizing is ±1arc.sec. Motion controller [8] of radial positioning unit has increment less than 1 nm and allows one to get ±30 nm accuracy when rotating spindle.

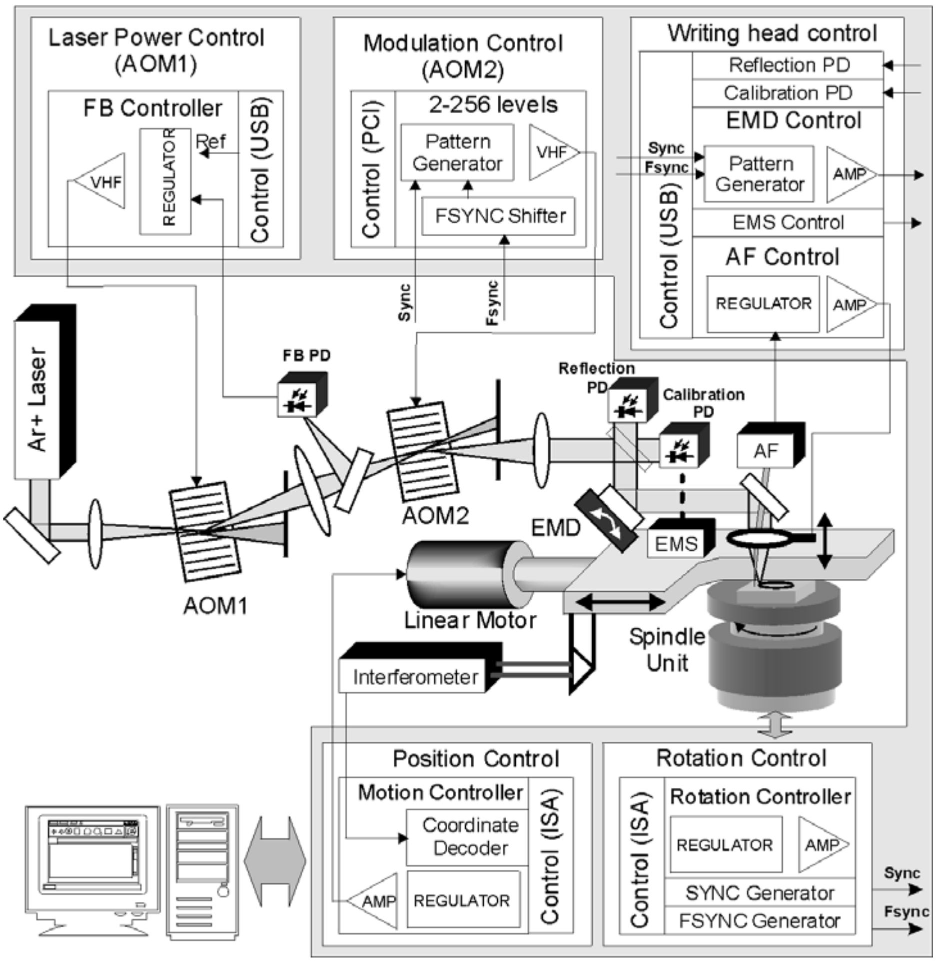


Fig. 4. Circular laser writing system

Writing is carried out by periodically replacing the writing head along radius at 600-700 rpm rotation speed of the substrate. Radial step between adjacent tracks was 0.2-0.5 μm. Laser radiation is modulated by acousto-optic modulators and enters into the focusing objective through the optical system mounted on the mobile precision air-bearing stage. The objective forms a spot on the substrate surface. The spot diameter is about 0.5 μm (at FWHM). Autofocus control system maintains constant size of light spot. The AF system consists of an electromagnetic actuator with a focusing objective and a defocus sensor with a diode laser (780 nm) and bicell photo-detector. The focused spots of the diode and writing lasers are separated by about 50 μm in the radial direction. This allows one to avoid autofocus errors caused by surface deformation in the writing process. The objective forming the recording spot is also used in an optical scheme for visual control of the substrate surface and the AF adjustment. Electromagnetic deflector (EMD) permits one to deflect the writing beam in the radial direction by the angle of up to ±1 arc. min. It is necessary to compensate for the spindle runout. Electromagnetic shutter (EMS) prevents parasitic exposure of the photoresist layer when writing is interrupted for calibration of the writing beam power.

Accuracy of the writing power control is a critical point for direct laser writing of continuous relief DOEs on photoresist and gray-scale masks. To ensure high modulation range, long-term stability, and reduce intensity noise we realized optical channel with two modulators. First of them is controlled by a feedback circuit using a signal from the photodetector (FB PD). AOM1 is used for power stabilization and power attenuation (12 bits) depending on radial position. Second AOM is intended for high-speed binary and analog modulation. This modulator has no permanent feedback loop, but its transfer function is calibrated before writing by the signal from a calibration photodetector installed behind it.

PCI-based pattern generator [9] transforms 32-bits data in the modulation signal for AOM2. This transformation is made in two steps. At the first stage the pattern generator converts 32-bit data format to two-parameter vectors: length and phase level. Gray-scale level of the vector can be varied from 0 to 255. Two clocks are used to synchronize the conversion process: the beginning of revolution (Frame Sync) and grid clock (Sync). If the number of clock pulses is sufficient to ensure 255 increments then the current zone will have 256 levels. At the second stage, a special Look-Up-Table (LUT) saved in RAM converts the values of phase levels to input data for a 10-bit digital-analog converter (DAC). The LUT table contains 256 10-bit values and is intended for linearization of the combined characteristic curve of the optical modulator and recording material. The 10-bit DAC forms analog signal for VHF driver of AOM2. Testing of the material described below gives the data that is used to calculate the transfer function reciprocal to the combined characteristic curve. This transfer function is saved in LUT and used for real-time transformation of the current phase level into the analog signal. Besides, the PCI-based pattern generator supports a pulse writing mode, which is very useful for circular writing systems while recording near the center of substrate rotation when scanning speed is very low. The pulse writing mode will be discussed in detail below.

Control of spot size and waist position

The minimum waist diameter (usually referred to as the spot size) is defined by numerical aperture of the focusing lens and input beam diameter. If high spatial resolution is not required (microoptics fabrication) it is useful to increase the spot size for accelerating the writing process and smoothing the profile roughness. Changing the focusing lens results in the necessity of optical and electronic readjustment of autofocus. Therefore, we use a beam expander to create a parallel beam after the second modulator. It allows us to change the spot size in the range 1:3, which is enough for most applications. Waist position is controlled in the writing system by an autofocus (AF) system. This system must be relative (not concerned with the position of minimum waist diameter of the writing beam), because some writing technologies require getting a minimum waist diameter inside the light-sensitive material. Relative independence of autofocus control is reached by usage of an additional laser in the AF sensor. Another requirement for AF control is that the radiation of the additional laser should be focused at some distance from the writing spot. It is necessary for avoiding the influence of possible changes in the surface reflection or shape under the action of the writing spot.

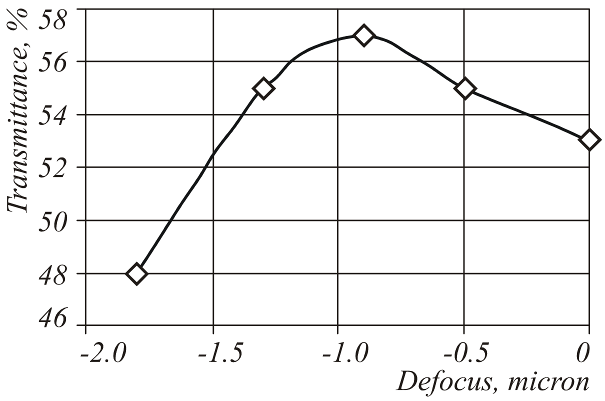


Fig. 5. Transmittance (at λ=514 nm) of areas exposed to the same beam power but at different defocusing from surface. Numerical aperture of the focusing lens is 0.65

The necessity to move the beam waist inside the light-sensitive layer arises when using multi-layer materials. For example, the LDW-glass has a light-sensitive layer (1-3 μm thickness) under the transparent surface layer (0.5 μm thickness). In Fig. 5, the focal plane on the surface is defined as 0 shift. Negative values indicate that the beam focus has been moved into the glass. Maximum transmittance at laser-activated decoloration of LDW-glass is obtained when the focusing lens is shifted about 1 μm down from where it focuses on the glass surface. The plot of Fig. 5 was measured for LDW-glass type I.

In CLWS the focal plane shift is specified by the controlling software before the writing of the element. This option is also used for finding an optimal position of the focal plane by maximizing the influence of the laser beam on the recording material, which can be defined for some materials by measurement of reflection or transmission change.

Scanning speed of the laser beam

The scanning speed of the laser beam is one of the most important parameters influencing the writing rate. The advantage of x-y writers compared to circular ones is a constant scanning speed of the laser beam. That makes easier calibration of the writing process. In circular systems the scanning speed increases with the radial coordinate. It permits the writing rate to be considerably increased with radius. For example, the writing rate reaches 1.57 mm^2/s on 100 mm radial coordinate at 600 rpm rotation speed and 0.5 µm radial step of circular scanning. As a result, the total writing time for a DOE of diameter 200 mm is about 11 hours, which is much less comparing to single-beam x-y systems. However, payment for the high writing rate is complexity of the beam power control. It is necessary to ensure high dynamic range of power modulation for direct writing on photoresists. Beam power control should compensate for changes of the scanning speed in the range 1:10000 and 1:100 range for the profile modulation. The total dynamic range of 1:1000000 cannot be ensured even with two optical modulators. Besides, the testing of the recording material near the rotation center is quite complicated because the beam scanning speed considerably changes even on the size of the test structure.

In order to avoid these problems combining the continuous and pulse writing modes was offered (figure 6). In the pulse writing mode, the amplitude modulation is added by pulse-frequency modulation. Period τ of pulses is calculated from the condition of constant overlapping value of the adjacent light spots:

$$\tau = \delta / 2\pi r \nu \ ,$$

where r is the radius of the written circular track, ν is the rotation speed of the substrate, δ is a constant linear distance between points of switching on the adjacent pulses.

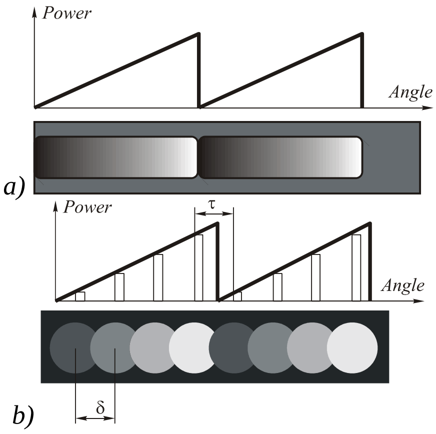


Fig. 6. Two modes of controlling the laser beam power for gray-scale writing: continuous mode (a) used far away from the rotation center and pulse mode (b) used near the rotation center

The constant overlapping at short pulse duration ensures the constant exposure dose at the same pulse amplitude independently of the radial coordinate. When writing on the photoresist, there is no need for attenuating the beam power with radius for the scanning speed up to 10-20 cm/s. The relation between power levels for continuous P_{cw} and pulse P_{pulse} modes can be estimated from the following simple ratio:

$$P_{pulse} \cdot D \approx P_{cw} \cdot \tau \ ,$$

where D is the pulse duration. The pulse duration is defined, on the one hand, by hardware constraints of the optical modulator and its driver, and, on the other hand, by the maximum power of the writing laser required to get the same exposure dose at short pulses as when using continuous exposure.

Behavior of materials with thermo-induced mechanism of recording differs from photoresists. If the surface of a recording material cools down between pulses the power required for writing does not depend on the scanning speed. However, the heated area of LDW-glass has no time to cool down completely between the adjacent pulses, if the duration between the adjacent pulses is less than 10 µs. The reason is in the low thermal conductivity of LDW-glass. Nevertheless, even in this case the application of the pulse writing mode is very efficient. Figure 7a shows the beam power as a function of the scanning speed coordinate for the continuous mode (a), and for pulse mode (b). Curves 1 and 2 depict different given transmittance levels of GSM. On the last plot the required writing power changes insignificantly (figure 7 (b)) with the radial coordinate, which makes easier testing the material and controlling the beam power.

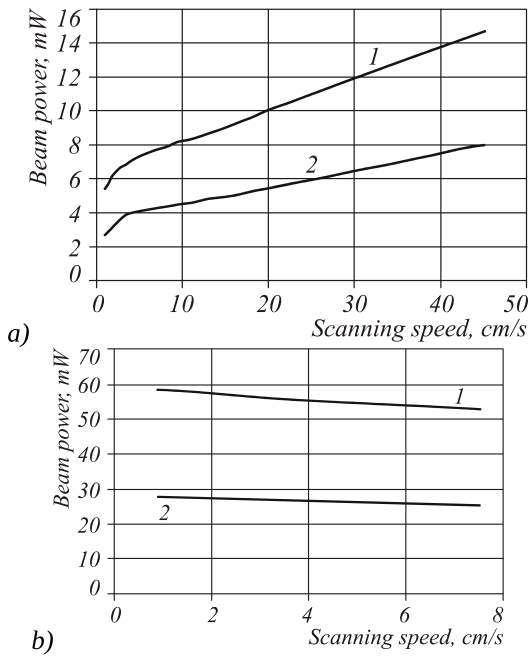


Fig. 7. Required laser beam power as a function of the radial coordinate for two transmittance values: curves 1 – for 33% transmittance, curves 2 – for 6% transmittance at 514 nm wavelength: (a) – continuous writing mode, (b) – pulse mode (pulse duration – 1 ms, d = 0.5 mm). Recording material – LDW-glass type I

Power modulation and surroundings dependent peculiarities

Action of the laser beam on materials with light-induced change of absorbance is accompanied by a return influence of changed transmittance on the quantity of energy absorbed in a colored layer. This effect exists for all aforementioned light-sensitive materials. However, for photoresists it is less noticeable because of a very small change of absorption at 457 nm wavelength that we used for laser writing. It is necessary to take into account that materials for GSM fabrication display this effect in several ways.

One of them concerns the overlapping of the area exposed by the focused laser beam and of the adjacent track exposed earlier. The interline spacing is recommended to be in a range of 0.25-0.5 times the spot size in order to avoid gaps between the tracks. We usually used 0.32 μm interline spacing at a track width of up to 1 μm. The surroundings formed before exposing the current track influence the achieved transmittance. The more overlapping, the stronger the influence because more energy can be lost falling into adjacent bleached track, and vice versa more energy can be absorbed falling into adjacent low-exposed track. However, greater overlapping decreases parasitic modulation of the transmittance distribution. Too much energy or insufficient energy at the boundary of gray-scale zones give rise to two types of "contouring" of the gray-scale diffractive zone: bright and dark "contouring". These phenomena are depicted in Fig. 8. Effects depicted in Fig. 8, (a) and (c) have surroundings reason, and effects depicted in Fig. 8b and d arise from power modulation.

The bright "contouring" arises when exposing the gray scale zones with maximal transmittance at the starting zone boundary. The first scanning line of the beam with high power on the zone border gives higher transmittance than next lines with the same power, because this first track falls into high-absorbing area (Fig. 8a). Surface even melts on the first track. On the following tracks the field exposed to the beam falls partially into the decolored previous track, and a significant part of the beam energy travels through the glass without being absorbed. The same effect is observed when power sharply decreases with time (Fig. 8b). Local melting of the glass surface on the zone borders results in the formation of surface ridges. Surface ridges and transmittance peaks scatter actinic radiation during printing of GSM along the zone borders and sharply worsen backward slopes of phase diffractive zones. This problem is not solved completely even by increase of the maximal transmittance in gray-scale zones up to the highest possible one, because melted ridges scatter light anyway. When the beam power increases from track to track (Fig. 8b) or with time (Fig. 8d), the bright "contouring" does not appear. However, the dark "contouring" can occur in this case (Fig. 8c, d). When the minimal transmittance in a gray-scale zone is chosen considerably higher than the transmittance of unexposed material the beam power on the scanning line following the line exposed with high power can be insufficient to get this minimal transmittance (Fig. 8c, and similar case for power modulation – d). This type of "contouring" is easily avoided by reduction of minimal transmittance in gray-scale zones to the transmittance value of the unexposed area.

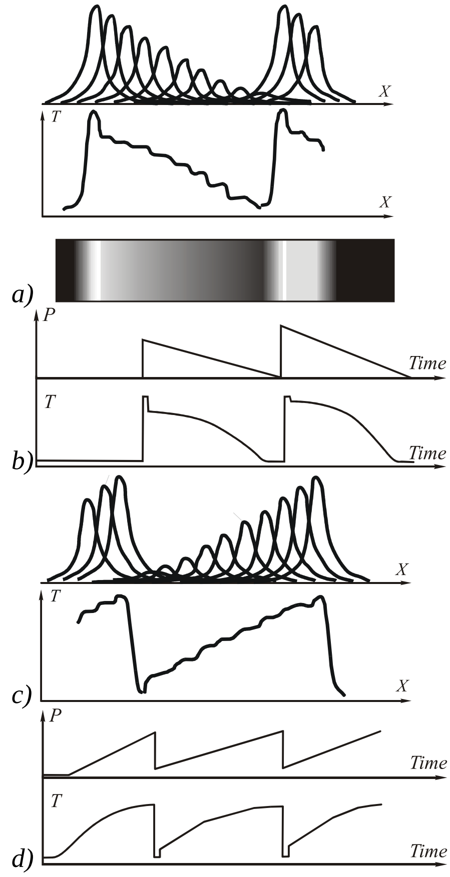


Fig. 8. Bright (a and b) and dark (c and d) „contouring": (a) and (c) depict the influence of track overlapping on transmittance distribution, (b) and (d) depict the influence of power modulation on transmittance distribution. T – transmittance, P – beam power, X – coordinate across beam scan direction (arrow of X axis indicates direction of shift of scan trajectory)

Elimination of "contouring" effect

To eliminate "contouring" caused by surroundings it is necessary to keep the information about the previous scanning line for the subsequent comparison of it with the current written line. If the comparison finds out parts with minimal transmittance on the previous line the beam power must be decreased on the adjacent parts of the current scanning line. We realized this type of compensation in the controlling software. However, in many cases the "contouring" because of surroundings does not influence noticeably the performance of GSM with arbitrary topology since it evidently appears if the laser beam goes along the zone boundary during long time. It is more important for such a situation to solve the problem with the "contouring" effect caused by the beam power modulation.

Several methods can be applied to eliminate this sort of "contouring" (Fig. 10). They are all based on smoothly increasing the temperature by forming a special transient process at the front of the beam power jump. The duration of the transition process depends on the scanning speed *V* of the writing beam. This dependence can be evaluated as a crossing time by writing beam for a distance equal to half recorded line width *W*:

$$\tau_f = W/2V .$$

The variant depicted in Fig. 10a is easily realized for x-y systems as a hardware-based frequency filtration of the modulating signal for smoothing the transient process at the fronts of light pulses. For circular systems, the duration of the transient process depends on the radial coordinate of the writing spot, and therefore a controlled modification is required. Variant (b) is identical to the method for eliminating ”contouring” because of surroundings. This method is easily realized by a program way, but its hardware-based realization is complicated. The complexity of hardware-based realization consists in the necessity to control the intermediate power level and duration of holding this level. Both parameters depend on the beam scanning speed and on the chosen transmittance range for GSM. The variant (c) is easily realized by a hardware-based way. Besides, this method allows receiving relative independence on a maximum power level using in a gray-scale zone. We tested this method and have shown its applicability. From the software realization point of view, the method is disadvantageous, because it is necessary to add 2 additional vectors for each diffractive zone.

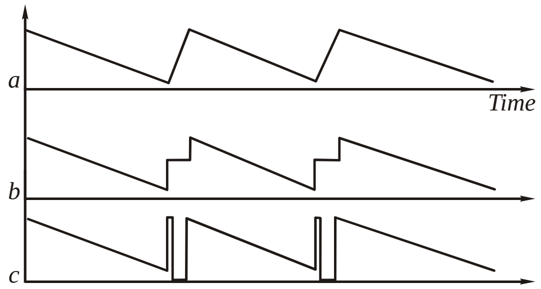


Fig. 10. Different variants of front modification at beam power modulation

The experiments have proved the applicability of the method: the “contouring” of the diffraction zones was eliminated. The microphotograph of a segment of a GSM made in the light transmission microscope is shown in Fig. 11a. Fig. 11b shows white light reflection microinterferogram of the same segment of the GSM. Left and right sites (in relation to vertical line) were written with opposite gradient of beam power. Typical “contouring” peaks on interference fringes caused by melted ridges are absent in Fig. 11b.

Influence of power modulation on characteristic curve

Experiments with the writing of several linear gratings with different periods and opposite gradients of beam power change were carried out to research the effect of beam power modulation on the characteristic curve of LDW-glass type I. The scanning speed of the laser beam was 50 cm/s. The form of the modulating signal is depicted in Fig. 12a.

Such a form was used for getting a reference level (Fig.12b) in each zone at defining the relative altitudes of profiles on an atomic-force microscope (AFM). The linear tilted segment of the modulation signal change was adjusted so that it would be far from saturation region of the combined characteristic curve of the acousto-optical modulator and LDW-glass. The gray-scale structures with periods 6 and 12 microns were exposed with 16 levels of beam power (including peak with minimum level), and 20 microns – with 32 levels.

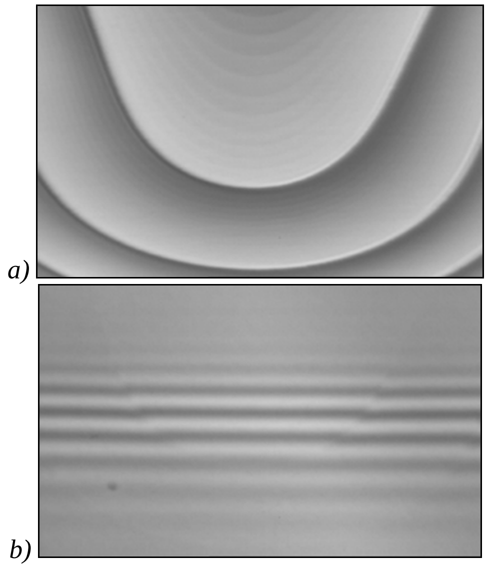


Fig. 11. Elimination of the „contouring“: (a) – microphotography (in transmission) of gray-scale mask written with modified front of light pulse; (b) – microinterferogram of the same surface in white light

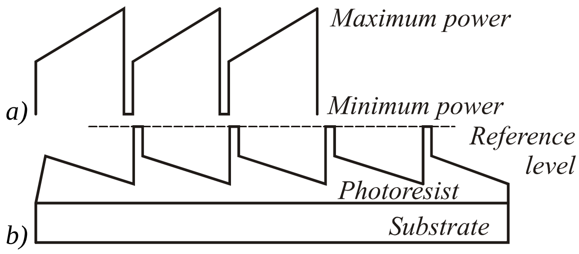
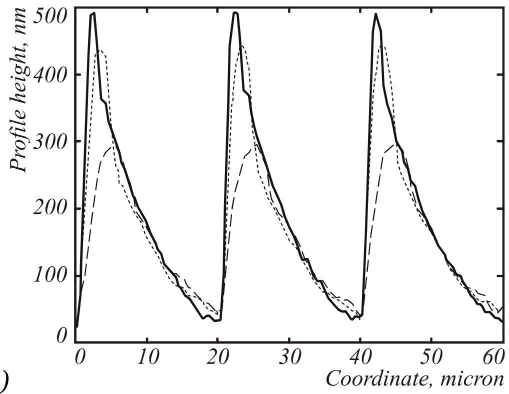
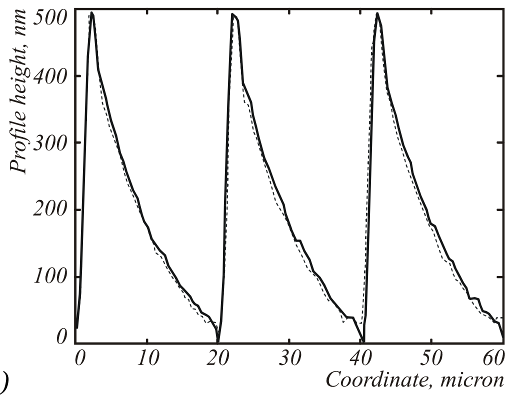


Fig. 12. The form of modulation signal (a) at writing of test GSM and expecting profile in photoresist (b) after printing of this mask into positive photoresist

The measurement by AFM of structures fabricated by contact printing of this mask in photoresist has allowed defining the influence of the “proximity” effect. Fig. 13a shows the profiles in photoresist with different periods. The profilograms for the gratings with period 6 and 12 microns are scaled on abscissa axis to period of 20 microns, thus allowing the direct comparison of the profile with different periods. The peaks on the profilograms correspond to the minimum of the modulation signal and minimum of transmittance on the test mask. The influence of the proximity effect starts essentially to appear at a period of grating less than 12 microns. This influence appears when the temperature maximum caused by the maximal power erases the colored specs on a neighboring area exposed with minimum beam power. As a result the contrast of GSM drops. The shape of the diffractive zones also changes. The influence of the proximity effect is less noticeable for periods more 15 microns. Therefore, it is enough to correct the characteristic curve for a range of periods from 4-5 micron (minimum for LDW-glass) to 15 microns.



a)



b)

Figure 13. (a) – AFM profilogram of microrelief in photoresist fabricated using test GSM with different periods: dashed curve – 6 μm, dotted curve – 12 μm, solid curve – 20 μm. Plots for 6 and 12 μm were scaled in horizontal direction to 20 μm period for comparing the profile; (b) – AFM profilogram of multi-level (32 levels) relief in photoresist fabricated using test GSM with opposite power gradient: dotted curve – negative gradient (decreasing power), solid curve – positive gradient

The writing of two gratings with identical periods but blazed in opposite direction has allowed to evaluate the difference of characteristic curves at writing with different gradient of laser beam power. Fig. 13b depicts the shape of a relief fabricated in photoresist by contact printing of gray-scale zones with positive and negative gradients for gratings with a period of 20 microns. The difference of microimage formation due to the sign of the beam power gradient (negative/positive) is insignificant and comparable with profile measurement errors. Therefore, at the modern stage of technology this effect can be considered as negligible because the contribution of other effects is much more appreciable.

Compensation of proximity effect

The proximity effect is caused by properties of recording materials with variable transmittance, though the similar effects are observed practically on all kinds of recording materials [10]. In the case of LDW-glass this effect is connected with thermal processes occurring in heat-sensitive layer due to erasing the colored specs. As mentioned above, the proximity effect appears for narrow diffractive zones, when the power gradient is high enough. Overall compensation of the proximity effect is practically impossible, at least without loss of mask contrast for all zones. To reduce the influence of this effect it is necessary to change the transfer function that is saved in LUT of the pattern generator. Two methods for updating the transfer function are offered. Both methods are based on using the calibration data, which are obtained from the measurement of the transmittance distribution in test gray-scale structures or from profilograms of microstructures printed in photoresist from a test gray-scale mask. The tests for the proximity effect can be made once for each used type of the gray-scale recording material, and then it is possible to scale experimentally obtained dependencies by results of calibration for the current blank. If the scanning speed in the laser writer is variable (as in circular systems), it is necessary to write such test structures at several values of speed in the entire range of changes. This is because the appearance of the proximity effect depends on the scanning speed.

The first compensation method is easier to realize. It is based on the common transfer function for all crossed diffractive zones on each scanning line. In that case the common transfer function is selected as a transfer function for any average period for the current line. This function is loaded in LUT of the pattern generator only for the same group of scanning lines. For the next group of lines, another transfer function can be loaded in LUT depending on the range of the periods in this group. The shape error of zone profiles depends on range of zone width. However it covers only a small class of diffractive elements and has low accuracy.

The second method is more complicated in realization and more time-consuming, because for using this method it is necessary to make DOE data processing according to a certain algorithm. This method is more accurate and uses several transfer functions for one scanning line. As mentioned above, the proximity effect appears for narrow diffractive zones with width less than 15 μm. Therefore, about 10 transfer functions are enough to cover the full range of the narrow zones. Assume that LUT can convert N phase values (256 – for our pattern generator). Dividing this array, for example, into 8 parts, we can use 8 transfer tables (functions) with N/8 values. In this case, the number N/8 means the maximum quantity of phase levels in DOE.

The necessary recalculation of data for each line is a disadvantage of this method. The algorithm of recalculation can be based on the analysis of diffractive zone widths along the scanning trajectory. It should be carried out during calculation of phase on the scanning line. The phase range for every diffractive zone on the current track is assigned according to tilt of designed phase profile (Fi.14a and b) and phase levels are shifted by value K=n*N, where n is the number corresponding to tilt of the diffractive zone, N is the number of phase level at writing. (in figure 10. b n=2, N=128). LUT is divided into a necessary number of conversion tables of length N, where the transfer curves are stored for every sort of tilt (Fig. 14c). Further, the pattern generator converts data to a modulation signal for the optical modulator (Fig. 14d). The controlling signals for the first and second zones will be different and more suitable for their gradients.

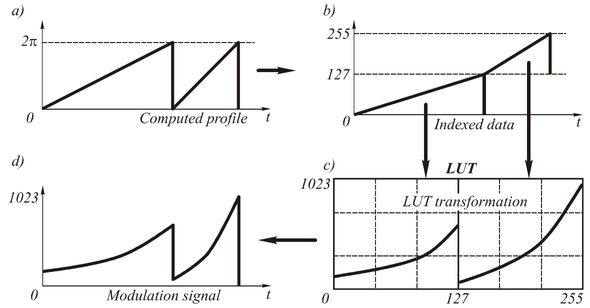


Fig. 14. An example of proximity effect compensation with two transfer functions in LUT

Software realization

The considered algorithms of the writing beam control are supported by the complex of CLWS software environment, developed on x86 platform and working under Windows2000 operational system. The CLWS software complex provides the whole work cycle from system testing up to DOE writing and keeping all operations performed in the electronic journal. Software environment has a hierarchical modular structure represented in Fig. 15. The interaction of the modules is organized by means of formally defined program interfaces that allow one to modify or replace any module without influencing the general structure of the software as a whole.

The software has the following basic modules:

- Graphic User Interface module gives the interactive interface used by the operator for system controlling.
- Control Programs Library provides a set of program modules each of which is intended for the following tasks: testing of the system, writing of binary DOEs, photo-electric testing of light-sensitive materials, writing of grayscale or multi-level DOEs.

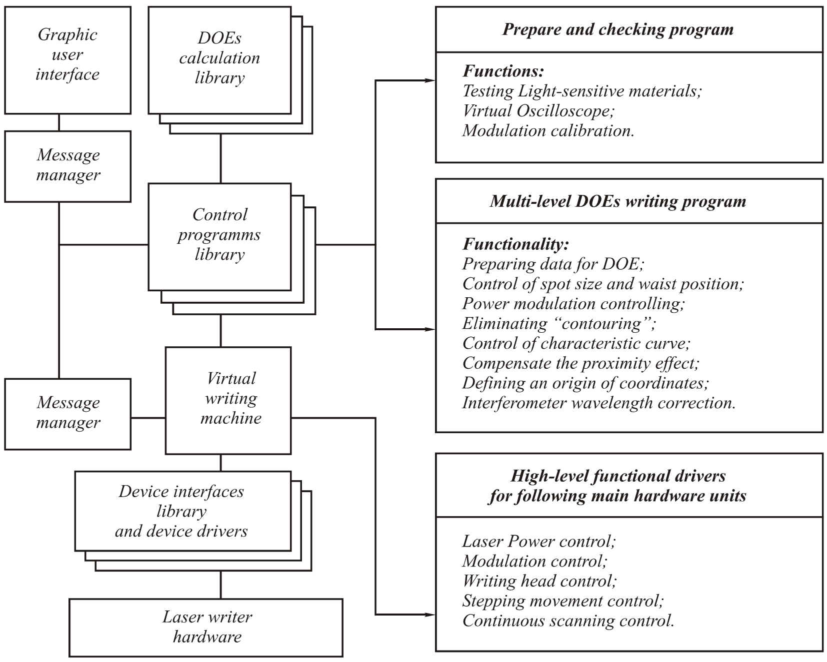


Fig. 15. Hierarchical modular structure of CLWS software environment

- Message manager module gives an opportunity for remote access of Graphic User Interface to one or several Control Programs by means of a local or global network, which permits remote monitoring and system controlling during the work cycle after installation and adjustment of the substrate.
- DOEs Calculation Library is used by Writing Control Program for calculation or reading of previously calculated data from the disk. DOEs Calculation Library can be extended without change in Writing Control Program. It makes the software more universal and flexible.
- Virtual Writing Machine provides high-level functional drivers for all laser writer hardware units. Writing Control Program controls these drivers by formalized program interfaces, which permits one to separate low-level hardware drivers from Control Program.
- Device interfaces library and device drivers ensure access to hardware of laser writer. Device manager gives an opportunity to configure Virtual Writing Machine by means of its connection to given types of Device Interfaces. It helps to replace or modify the Laser Writer hardware without rebuilding the high-level software.

Consider in more detail the Control Programs Library because it concerns the algorithms of laser beam controlling. The preparing and checking program is used for preliminary operations before writing. This program allows defining the optical modulator transfer function and photoelectrical measurement of the characteristic curve of the light-sensitive material. Oscillograms from certain control points of the electronic blocks can be observed using a Virtual Oscilloscope feature with mathematical processing functions such as spectral analysis, statistical processing, etc. Multi-level DOE writing programs are intended for multilevel writing using methods described above. The functionality of these Control Programs is represented in Fig. 15. The DOE data preparation is carried out using the described algorithms for influence reduction of "contouring" and proximity effects. Besides, the writing program controls the waist position, power modulation and carries out a periodical zero-point calibration (rotation center search) [11].

Control Programs work with a virtual Laser Writer independently of its specific hardware realization. The above-described CLWS can be formalized with the aid of the Virtual Writing Machine based on 5 main hardware sub-systems (see Fig. 4). Stepping movement control is responsible for Position Control unit, and Continuous scanning control for Rotation Control unit. This software package can be used also for controlling other writing systems (including X-Y writers), if their hardware can be formalized similarly to the interface of Virtual Writing Machine. In this case only change of Low-Level hardware drivers is required.

Conclusions

Scanning laser writing systems are very promising tools for direct writing of 3D microrelief or gray-scale masks. However, the capabilities of laser writers can be realized at an accurate and flexible computer control of writing beam parameters (beam power, spot size, waist position) taking into account complexity of behavior of light-sensitive materials. Use of circular scanning in the laser writer permits one to increase considerably the writing rate but it imposes additional requirements onto the dynamic range of power modulation. Nevertheless, the advanced computer control of the writing beam in the laser system CLWS developed in IA&E SB RAS (Novosibirsk) permits one to eliminate or reduce the influence of the above-mentioned effects. This system of computer control has the following capabilities:

- shift of the beam waist position inside the recording layer;
- high-dynamic range of modulation on account of using 2 acoustooptical modulators
- division of the modulation function between the modulators: compensation of change of scanning speed and noise suppression – first AOM, high-speed modulation according to given 3D microstructure – seconds AOM;
- combining the continues exposure mode and pulse mode with pulse-frequency modulation;
- program generating of a special transition process in the beam power modulation to reduce „contouring" effect at writing on gray-scale materials;
- dynamic change splitting LOOK-UP-TABLE of pattern generator to several parts corresponding to different tilt of diffractive zones (compensation of proximity effect) and different profile depth in phase-matched DOEs.

Due to these features CLWS is able to fabricate high-efficiency arbitrary DOEs, microoptical elements and gray-scale masks in short time and with accuracy corresponding to modern requirements.

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Computer controlling of writing beam in laser microfabrication of diffractive optics

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Abstract

Laser microfabrication of diffractive optics with continuous relief is based on the direct local action of focused laser radiation on the recording material. Control of writing beam parameters (beam power, spot size, waist position) is one of the main tasks in microfabrication using laser writing systems. Method of the control defines the correspondence between the fabricated microrelief of the diffractive optical element and a designed one. Complexity of this task consists in the necessity to take into account a wide range of factors: laser irradiation noises, non-linear characteristic curve of recording material, finiteness of spot size, influence of power modulation and surrounding on beam energy absorption, influence of beam waist position according to recording layer, dependence of characteristic curve of recording material on beam scanning speed, etc. In the present paper we consider a number of methods for computer controlling of writing beam making it possible to compensate or reduce the influence of these factors and improve the quality of DOE microfabrication. The results of experimental application of the developed methods to circular laser writing systems are discussed.

Keywords: diffractive optics, microfabrication, direct laser writing, circular laser writing system.

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