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TECHNOLOGY OF COMPUTER-SYNTHESIZED OPTICAL ELEMENTS

LASER PLOTTER OF KINOFORM OPTICAL ELEMENTS

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Abstract—The concept and applications of a computer-controlled image plotter are considered. The block diagram of the setup is presented, accompanied by a discussion of the hardware and software issues and the problems of recording assorted kinoform masks on thin chromic films.

1. INTRODUCTION

Kinoform optical elements are phase information masks that contain information about the wavefront in the form of phase retardations which do not exceed the wavelength [1]. Kinoforms may be placed midway between the diffraction and refracting optical elements. The phase structure of a kinoform mask is developed on a computer. Precision photoplotters record this phase pattern onto phase sensitive materials as phase retardations in real time [2] or onto light or heat sensitive materials in the form of blackening densities or sets of amplitude masks that will be used for phase relief synthesis [3, 4].

Computer controlled precision image plotters [5–7] are now available in the field of hologram fabrication, and these have paved the way for the preparation of kinoform masks that can focus, deflect, separate and transform light beams.

The present paper describes the concept and the applications of a computer-aided laser image plotter. It considers the block diagram of the principal electronic and optical systems of the setup, and presents the corresponding technical data. An ample space is devoted to the description of the software and the technology of recording an assortment of kinoform masks.

2. BLOCK DIAGRAM AND SYSTEMS OF THE PLOTTER

The laser plotter records kinoform masks on a point-by-point basis. The plotter comprises two independent two-coordinate positioning systems, an electromechanical system to position the image carrier and an acousto-optical system to position the recording laser beam.

The main unit of the plotter (Fig. 1) is the two-coordinate electromechanical system driving the table (1) carrying a substrate (2) with heat- or photo-sensitive material. The coordinate table moves in the horizontal plane on four pneumatic supports in two mutually perpendicular directions. The position of the table along the x, y axes is monitored by two laser interferometers (3, 4). These interferometers are placed so that their beams are directed along the edges of the measurement guides (5, 6) fixed along the table. Two corner retro-reflectors (7, 8) in contact with the measurement guides are placed in carriers to move along the working arms of the interferometers.

The source of light for both interferometers is a He–Ne laser (9). Having passed through the collimator (10) the laser beam strikes the penta prism (11) to be divided into two orthogonal beams of equal intensity directed at the interferometers.

The coordinate table is driven by linear d.c. motors (12, 13) integrated with the orthogonal guides along which the table travels.

An argon laser (14) is used to provide energy for the recording. The beam of this laser passes

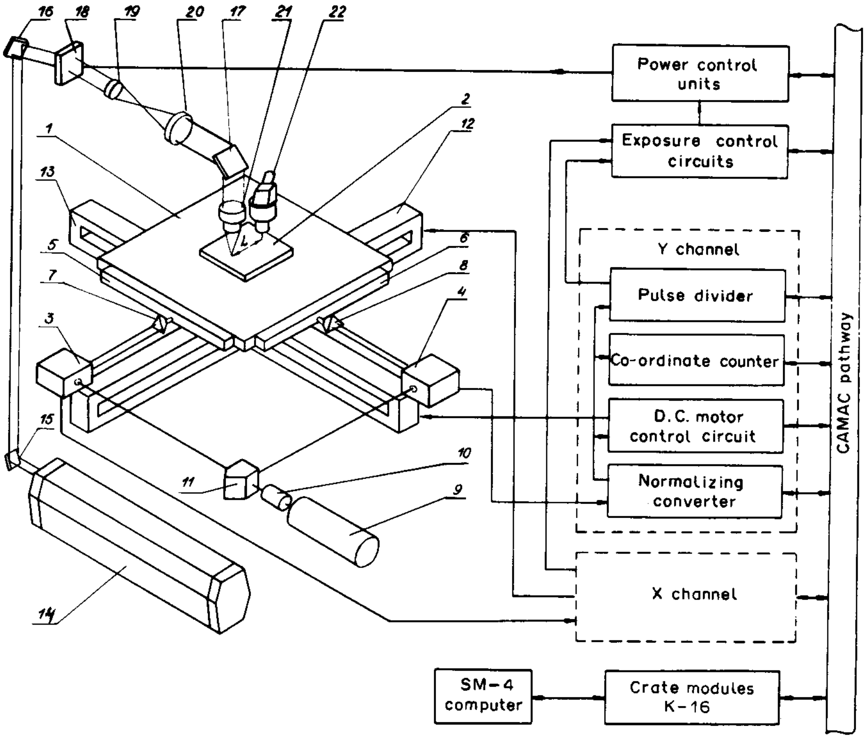

Fig. 1.

through the optical system comprising deflecting mirrors (15–17), a two-coordinate acousto-optic deflector-modulator (18), and lenses (19–21) and is focused onto the substrate (2).

The measurement and monitoring channel (22) employs the head of a metallurgical microscope (× 600) which is provided with an objective micrometer and a microphotographic attachment. The optical axis of this channel is displaced with respect to the image recording channel.

In order to record an image in the plotter:

(1) the "image carrier" of the substrate is moved mechanically with respect to the focused laser beam,

(2) the recording laser beam is moved about the (now) fixed image carrier in the array field (raster) of 100 × 100 pixels created by the acousto-optic system,

(3) the image carrier is moved mechanically and the recording laser beam is scanned or corrected across the motion of the substrate.

The electronic circuits of the system for locating the coordinate table and the recording laser beam, and the exposure control units, are housed in two CAMAC crates and hooked up to an SM-4 computer via the crate modules K 18.

The electromechanical table-driving system moves the table in steps of 0.08, 0.16 or 0.32 μm. It positions the table in the field of 420 × 420 mm within an accuracy of 0.5 μm. If the table is driven along one coordinate, the position holding error in the other coordinate is within 1.5 μm.

The electromechanical table drive system comprises two identical channels for X and Y coordinates, each of which contains a normalizing converter, a reversible counter of table coordinates, a linear d.c. motor control unit and a pulse divider with programmable division coefficient. The normalizing converter interfaces the laser interferometer and the digital units of the electromechanical positioning system. The table coordinate counter records the absolute values of table coordinates with respect to its initial position taken as datum. The d.c. motor control unit implements a dual mode control [8] in which the table is steered into a comparatively small zone (320 μm) by a bang–bang controller offering a quasioptimal speed, whereupon the accurate positioning is effected by a proportional-integral-derivative controller.

The pulse divider with a programmable coefficient of division governs the size of a quantized step of table travel $N \cdot q$, where N is the division coefficient given by the computer and q is the sampling rate formed by the normalizing converter of the laser interferometer.

The acousto-optical system for laser beam steering comprises a number-pulse adder and a digital frequency synthesizer [9].

The position of the laser beam at the output of the acousto-optical deflector-modulator is governed by the code recorded in the number-pulse adder. The latter has three modes of operation:

(1) storage of the code of a number which is changed by the computer;
(2) adding of the number code, written in it in advance, to the number of pulses from the generator of a programmed number of pulses;
(3) adding to the number code the number of pulses from the normalizing converter.

The storage mode (1) is used in recording the image on a carrier when the latter travels with respect to the stationary laser beam or when the beam travels about the carrier. The codes of the numbers defining the position of the laser beam are changed in the adder by command from the computer.

The addition mode (2) allows higher recording rates to be used in covering rectangular areas of greater size than the dimension of the light spot of the image carrier.

Finally, the mode (3) allows both higher rates and higher accuracy to be achieved in recording unidimensional linear gratings. This gain of speed and accuracy is enabled as the result of the dynamic compensation of errors of the electromechanical table-drive system by the high-speed acousto-optic deflector of the recording laser beam.

The exposure control system comprises a 1 MHz quartz pulse generator, a clock and a pulse switch which selects a driving pulse train for one of the d.c. motors according to the given division coefficient. These components allow exposure pulses to be transmitted at a repetition rate of 1–128 μs.

The laser plotter operates with the basic package of an SM-4 minicomputer including a processor with a memory dispatcher, a 96 K-byte RMA memory, floppy disk stores and terminals.

3. THE SOFTWARE

The associated software implementation was based on the RSX-11M operating system (OS PB 2.0). It was meant to support the experimental study of plotter performance and plotter modes in laser recording on various heat- and photosensitive materials as well as the preparation of kinoform masks. It consists of system support programs and special purpose software.

The system support software of the plotter employs assembler service routines. These routines take charge of regulating the electronic units of the plotter systems, data flow between these systems and the computer, and translation of integer numbers into a real format and vice versa. The system software also includes a program pack for mathematical support of the plotter adapted to the plotter implementation [10]. This pack comprises more than 20 programs. Three of them, CANAL, LEAF and TRA have been modified as follows.

The CANAL subprogram is in charge of the operating modes of the plotter. It determines the recording regimes, specifies the time of exposure, sets up the steps in the x and y drives of the table, evaluates the zones of mismatch in these coordinates and the delay time in setting the electromechanical positioning servo system. When all this is over, the table is deemed set in the desired position.

The subprogram LEAF specifies the area of writing that remains fixed until a new area of drawing is ordered. The size of a drawing area is limited by the field of the coordinate table and cannot exceed 420 × 420 mm. The subprogram involves four parameters. Two of them give the size of drawing area in millimetres in the x and y coordinates. This area can be embraced by a frame; for this purpose the third parameter must have the value TRUE. Operation outside this area is forbidden. Escape beyond this area is controlled, and depending on the value of the fourth parameter this control may be "hard" or "soft". In the hard control mode (FALSE), any attempt to drive the coordinate table beyond the given area is treated as an error. Under the soft control mode (TRUE), the system draws the area of image being within the area of drawing, while the lines outside this area are ignored.

The TRA subprogram plays its part in image recording by moving the coordinate table with respect to the laser beam, causing the carrier to travel from one position to another. The initial coordinates for this subprogram are the coordinates of the table at the instant when this subprogram is addressed.

The coordinates of a point to which the table is driven are specified by first two real parameters of TRA. The third parameter is an integer between 1 and 10. The value of this parameter defines the swing of the laser beam scan across the travel of the coordinate table. The fourth parameter is another integer. It defines the state of the modulator. If it is a 1, the table traverse to the new position results in drawing a line. If it is a 0, then the traverse is idle.

This package of subprograms written in FORTRAN IV facilitates the development of programs for recording kinoform masks.

The special mathematical support software includes test programs that help to improve the laser recording technology on various materials. It also includes recording programs for special optical elements. Photographs of some masks prepared on the plotter will be given below.

4. MASK RECORDING TECHNOLOGY

Kinoform masks were written on 300–1500 Å chromic films deposited on glass substrates. Laser radiation forms in these films a latent image [11] that can be revealed by the subsequent chemical processing of the films in special etching tanks [12]. The areas irradiated by laser light are subjected to intense oxidation. These areas are etched at a much slower rate than those not subjected to irradiation, and therefore remain on the substrate after etching.

Test runs in which unidimensional diffraction gratings were made indicated that a constant width of a line can be maintained at recording rates up to 5 cm/s with exposure length at each point not longer than 10 μs. Line width depends on the power of the argon laser. For irradiant powers of 30–80 mW it varies from 2 to 5 μm.

Figure 2(a) shows a test diffraction grating with a period of 6 μm. The waviness of lines was caused by starting a line before the transient in the electromechanical positioning system has died out. To improve the accuracy and raise the speed of recording we used dynamic compensation of position error in the electromechanical system, employing the acousto-optical system of laser beam deflection. This method allows a next line to be recorded without waiting until the transient of the carrier positioning dies out. This transient is monitored by the computer as it continuously observed error values. When the error increases so much that it cannot be compensated any longer by deflecting the recording laser beam, a command is issued that causes the carrier to be moved in the direction of recording of the line. When this happens, the code of the number defining the position of the beam is corrected in the number-pulse adder by the pulses of the normalizing converter of the interferometer. This method of recording also allows the compensation of errors

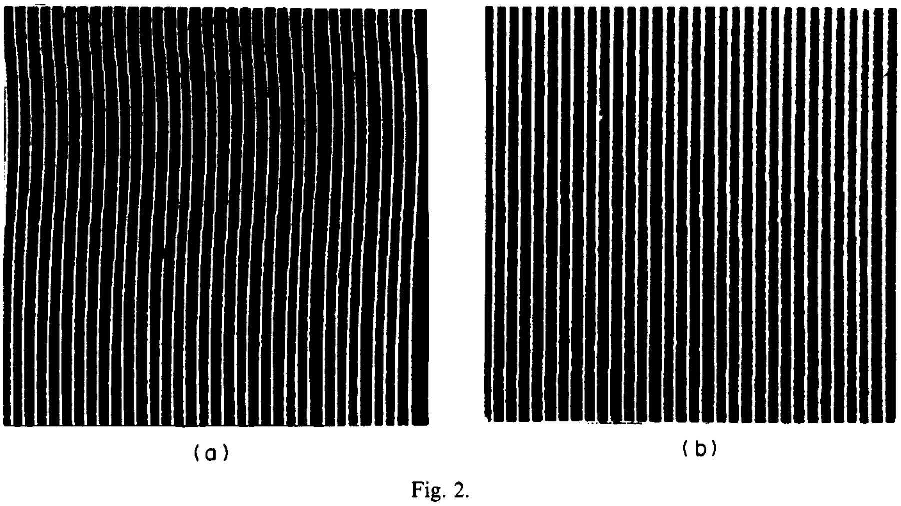
(a) (b)

Fig. 2.

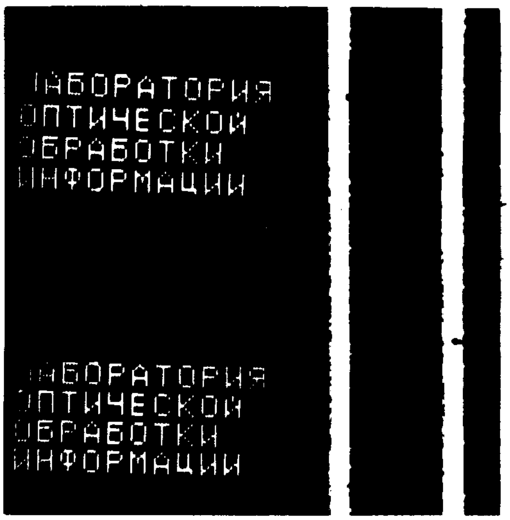

Fig. 3.

which may be caused by occasional disturbances (vibrations) after the positioning process is over. The capabilities of the method are demonstrated by the test record of a grating shown in Fig. 2(b).

Heavier lines (Fig. 3) were obtained by recording parallel lines with 50% overlap. The generic thin lines were recorded by scanning the laser beam across the motion of the carrier. The width of a line may be varied in a programmed manner in the range $(1\text{–}10)\cdot w$, where w is a single line width. The text in Fig. 3 was recorded in the field of the acousto-optic deflector with the stationary coordinate table. The period of the deflector was 3 μm, and the letter size 12×18 μm.

5. EXPERIMENTAL

The thermochemical technology of laser recording was employed to prepare the masks of cylindrical Fresnel lenses, optical elements with cross and square impulse responses, a disc scanner of the laser beam that is simultaneously focused in the plane of scan, and masks of diffraction gratings.

Fresnel-lens based kinoform masks are simplest masks (both single and crossing) to prepare on the plotter. A cylindrical Fresnel lens is an array of alternate transparent and opaque zones in which the start of zone i is the end of zone $i-1$. The initial and final values, R, of the ith zone were calculated by the expression

$$R_i = (m\lambda F + m^2\lambda^2/4)^{1/2}$$

where F is the focal length of the lens for a source of wavelength λ, and $i = 1, 2$, etc. are integers. The odd values $m = 2\cdot i - 1$ define the initial values and the even $m = 2\cdot i$ define the end values of opaque zones.

Figure 4 shows a mask of two Fresnel lenses intersecting at right angles and the response of this optical element to a light impulse. The focal length of this lens is 200 mm, the aperture ratio 1:10. It is designed to focus a plane parallel laser beam of $\lambda = 0.63$ μm. The number of zones in this element is limited. Photometric measurements of the width of the lines producing the cross gave 12 μm which exactly coincides with the calculated value. The time to record a mask of 1000 zones was 40 min.

The mask of a disc scanner with linear scanning and simultaneous focusing of the beam is shown in Fig. 5. Physically this mask is an off-axial strip of a Fresnel lens twisted into a ring by the transformation of the coordinate zones of the lens from a Cartesian to a polar system of coordinates [13]. Experiments with the disc diffraction scanner using this mask revealed the following performance data: length of a scan line, 15 mm; plane of scanning at distance 200 mm from plane of disc rotation; number of pixels resolved for a He–Ne laser beam, 100.

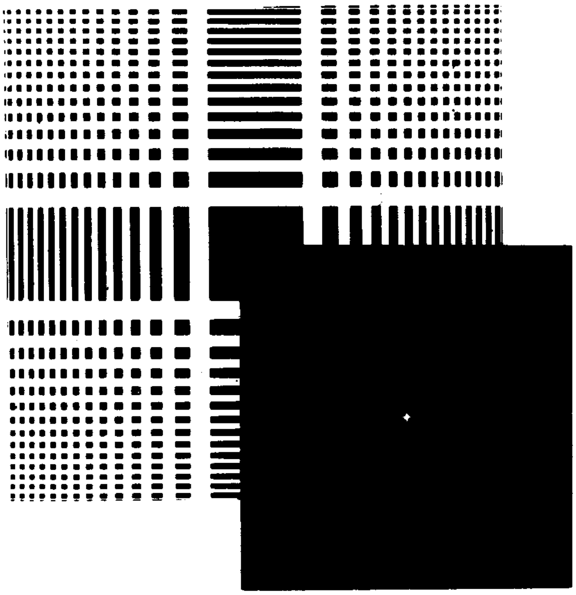

Fig. 4.

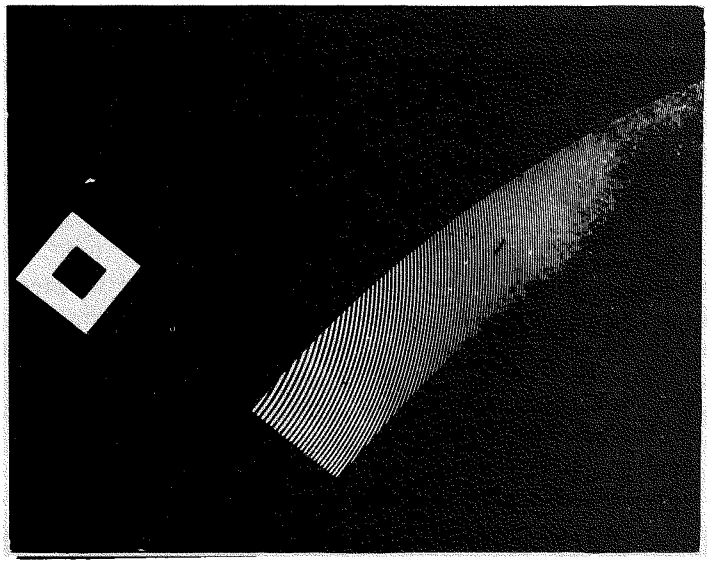

Fig. 5.

6. CONCLUSION

The block diagram, hardware and software of the laser plotter of kinoform elements have been discussed. A method of mask recording was demonstrated that involves a dynamic compensation of errors of positioning of the electromechanical system with the aid of a high-speed acousto-optical system. The latter system deflects the write beam across the direction of motion of the image carrier. The plotter offers a large field of recording, precise metrological characteristics, and, in tandem with the thermochemical technology of image recording onchromic films, it can be used to prepare a variety of kinoforms.

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