Device Photolithography:

The Primary Pattern Generator
Part I–Optical Design

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I. INTRODUCTION

The basic design concept of the primary pattern generator (PPG) is the production of a linearly scanning, small, constant-size light spot. The scanning system consists of a regular polygonal-prism mirror which rotates about its axis of highest symmetry. The mirror faces are used sequentially to reflect a collimated light beam into a lens (for example, the scanning lens of Fig. 1). The collimated light is focused to a spot which scans a line in the focal plane of the lens as the polygonal mirror rotates. Located in the focal plane of the lens is a flat, glass photographic plate. The glass plate is moved by the desired scan line separation during the time required to bring the succeeding mirror facet into proper position.

The collimated beam incident onto the rotating mirror is formed by the scanning lens from a diverging beam obtained from a laser. The location of the reflecting mirror facet must be close to the aperture plane of the scanning lens in order to insure that the mode is not truncated by the physical lens apertures after the light is reflected from the mirror facet. Translation of the reflecting facet will not affect the position of the focused spot; the spot position is uniquely determined by the directions of the incident collimated beam and of the reflecting mirror facet relative to the optic axis of the lens. A barrel distortion is designed into the scanning lens such that the linear velocity of the focused spot is proportional to the angular velocity of the rotating mirror.

The machine just described is basically analog along its fast-scan axis, although it is digital along the slow (substrate translation) axis. Since the required reproducibility is greater than the required accuracy,

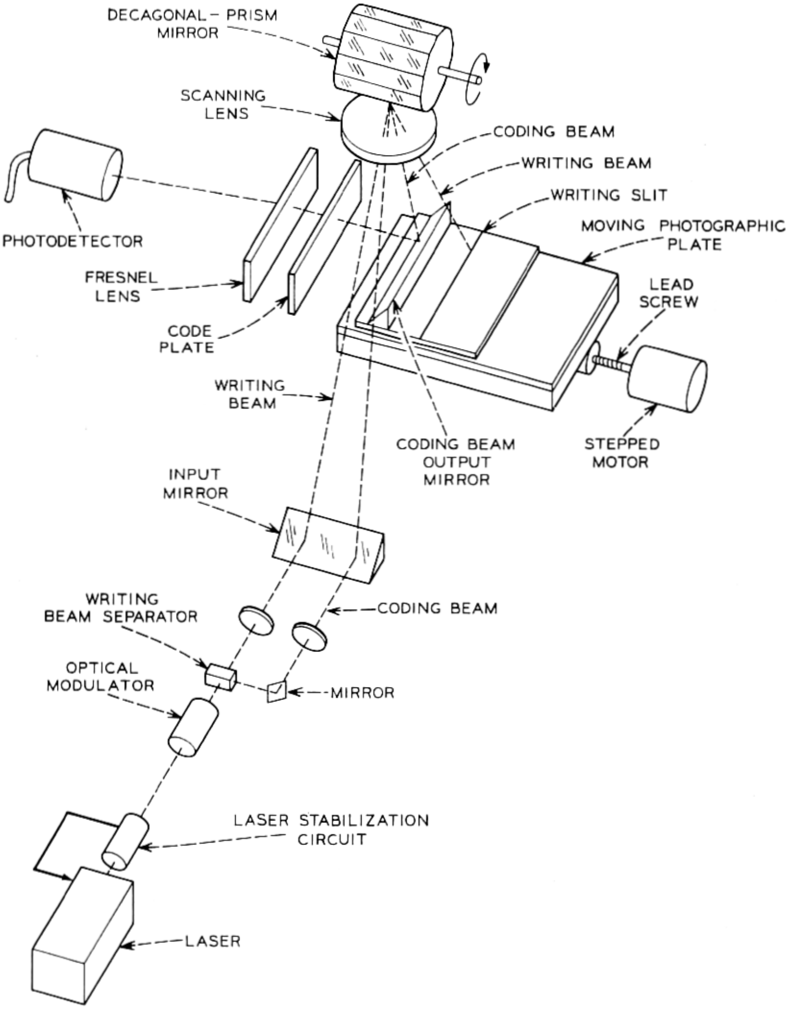

Fig. 1—Schematic of primary pattern generator.

a digitally operating machine is more desirable than an analog machine. The fast-axis can be made digital by using a separate beam to scan over a grating type of code plate. The location of this beam on the code plate tracks the position of the writing beam and generates timing pulses for a control computer. The resolution of the code plate must be as good as the reproducibility required; that is, the code plate system must be capable of resolving 26,000 positions per scan length.

The pattern size is principally established by the capabilities of the scanning lens. The minimum spot diameter is determined by the approximate diffraction limitation of equation (1),[1] obtained when a lens aperture is uniformly illuminated.

$$I(r) = \left(\frac{2J_1(x)}{x}\right)^2 I_0 \qquad x = \frac{\pi r}{\lambda f_n}. \tag{1}$$

Here, f_n is the f-number of the lens forming the image $I(r)$; r is the radial distance from the image center; I_o is a constant proportional to the intensity illuminating the aperture; and λ is the wavelength. Using this relation, we approximated the half-power diameter of a spot formed by such an illuminated lens to be

$$D \approx 0.58 f_n \qquad D \text{ in } \mu\text{m}, \lambda = 520 \text{ nm}. \tag{2}$$

We now consider that the polygonal mirror will have some wobble to its motion, and further, that all faces of the mirror will not be exactly parallel to the rotation axis. Consequently, to reduce the effect of these mirror defects on the pattern, the scanning lens should operate with as large a field angle as possible. This wide-angle requirement limits the f-number for which diffraction limited performance can be obtained in a lens. For a 48° field angle, calculations made by Tropel, Inc.,* showed that a minimum f-number of 13 could be used for good performance of the coding beam over the field. Using equation (2), a spot size of 7.5 μm half-power width is thus obtained; this will be approximately the size of the address unit. Since 26,000 address units are required for a full scan line, an address size of 7.0 μm will allow the full pattern of 26,000 by 32,000 address units to fit on a standard 8″ × 10″ photographic plate.

To produce a complete pattern in less than 10 minutes, each of the 32,000 scan lines must be traversed in less than 20 ms. Since the writing-beam diameter will be less than twice the address spacing, the beam must sweep its own diameter in less than 800 ns. To produce sufficient exposure on high-resolution emulsion[2] requires a beam brightness obtainable only from a laser. However, the writing-beam power required is only 20 μW. Orthochromatic emulsion is desirable since it will allow a safelight environment. Thus an argon laser,[3] operating at 5145 Å wavelength was chosen as the light source.

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* Located at 52 West Avenue, Fairport, New York.

It operates in the lowest transverse mode,[4] thus the radial intensity distribution anywhere in the beam path is gaussian. The output of the laser is stabilized by feedback through the laser power supply to a variation of less than 1 percent, thus insuring uniform exposure of the photographic plate.

II. THE PHOTOGRAPHIC EMULSION AND THE EXPOSURE PROCESS

The sweep of the writing beam across the photographic plate results in a variation of the exposure of the emulsion in a direction normal to the scanning direction. If we use the scanning velocity as v_0 and the intensity distribution of the scanning spot as

$$I(r) = \frac{2P}{\pi w^2} \epsilon^{-2r^2/w^2} \tag{3}$$

where P is the total power in the writing beam and w is the waist radius,[5] then taking the scan to be x-directed along the line $y = y_0$, the variation of exposure in the y-direction is obtained by integration, as

$$\begin{aligned} E(y) &= \frac{2P}{\pi w^2} \epsilon^{-2(y-y_0)/w^2} \int_{-\infty}^{\infty} \epsilon^{-2(v_0 t)^2/w^2}\, dt, \\ &= \frac{P}{w v_0} \sqrt{\frac{2}{\pi}}\, \epsilon^{-2(y-y_0)^2/w^2}. \end{aligned} \tag{4}$$

The next line will scan with y_0 changed by one address spacing and the exposure produced by this scan will be added to the exposure of the first scan. The total exposure produced by N scans is thus obtained by summing N displaced gaussians given by equation (4).

A similar analysis is used to obtain the exposure resulting from modulation of the writing spot. In this case, the beam is turned off at $x = 0$ for each scan. As a first approximation, we assumed the intensity of the writing spot to decrease with a relaxation time of $\tau = d/v_0$ where d can be interpreted as a rise distance in analogy to a rise time. The exposure caused by a single trace having the beam turned off at $x = 0$ becomes

$$\begin{aligned} E(x, y) = \frac{2P}{\pi w^2} \epsilon^{-2(y-y_0)^2/w^2} \Bigg[&\int_{-\infty}^{0} \epsilon^{-2(x-v_0 t)^2/w^2}\, dt \\ &+ \int_{0}^{\infty} \epsilon^{-v_0 t/d} \epsilon^{-2(x-v_0 t)^2/w^2}\, dt \Bigg] \end{aligned} \tag{5}$$

which is evaluated in terms of the error function and its complement.[6]

$$E(x,\, y) = \frac{P_0}{wv_0\sqrt{2\pi}}\, \epsilon^{-2(y-y_0)^2/w^2} \cdot \left[\operatorname{erfc}\left(\frac{x\sqrt{2}}{w}\right) + \epsilon^{-x/d}\epsilon^{w^2/8d^2}\left(\operatorname{erf}\left(\frac{x\sqrt{2}}{w} - \frac{w\sqrt{2}}{4d}\right) + 1\right)\right]. \qquad (6)$$

Application of this exposure to a high-contrast emulsion will result in the production of a density gradient at the boundaries of the exposed regions. The greatest magnitude of the gradient will occur very close to the contour of 0.5 optical transmission through the developed image. The task of determining the actual image formed by the exposure function of equation (6) is thus reduced to tracing the contour of the exposure necessary to produce 0.5 transmission and to evaluate the exposure gradient normal to this contour. A computer program was written to evaluate equation (6) over a matrix of points. Table I shows some of the results of these calculations. An exposure of 1.00 is used to produce the 0.5 transmission value.

For simplest operation, five scan lines or a five-address modulation should produce an image five address units in dimension. To obtain a best compromise between freedom from mirror facet wobble and maximum edge gradient, we chose to operate with a half-power writing beam diameter between 1.3 and 1.7 address units (9 to 12 μm). Equation (4) can now be used to calculate the beam power required to obtain proper exposure on various emulsions. For a spot velocity of approximately 16 m/s, 20 μw of beam power will produce a maximum exposure of about 120 ergs/cm². High resolution plate[2] requires over 1000 ergs/cm² for proper exposure. Eastman Kodak Company had an emulsion which reached proper exposure between 20 and 100 ergs/cm², although it was not a standard product. This emulsion, called Minicard,

TABLE I—VARIATION OF EXPOSURE PARAMETERS

Half-Power Spot Diameter	2.7	2.0	1.7	1.3	2.0	1.7	1.3
Peak Exposure of a Single Scan	1.1	1.8	2.5	4.7	0.9	1.1	1.4
Width for 5-Scan Lines	6.0	6.0	6.0	6.0	5.0	5.0	5.0
Gradient ($\partial E/\partial y$)	1.0	1.5	2.0	3.1	1.0	1.2	1.7
Peak-Exposure for Large Number of Scan Lines	2.9	3.7	4.5	6.7	2.0	2.0	2.0
Length for 5-Address Modulation	6.1	6.2	6.3	6.5	5.0	5.0	5.0
Gradient ($\partial E/\partial x$)	0.9	1.3	1.6	2.1	0.8	0.9	1.0

was available on special order; Eastman Kodak now produces 8″ × 10″ glass plates coated with Minicard emulsion.

The glass photographic plates must have a very flat emulsion surface. Fig. 2 is an illustration of the effect of plate camber. The emulsion surface will be held near the extremes of the scan line. However, plate camber will cause registration errors between plates because of the angular scan of the writing beam. The maximum angle made by the writing beam and the normal to the photographic plate is 15°. To produce less than a one-address-length error between X_1 and X_2 of Fig. 2, the plate camber must be less than ± 28 μm. This specification is safely met by Kodak microflat plates, but is very far from being met by the specifications of lower grades of glass plates.

III. THE ROTATING MIRROR AND SCANNING LENS

The dimensions of the rotating polygonal mirror are determined by the scanning-lens aperture. Since the *f*-number, field size and field angle of the scanning lens have been determined by equations (1) and (2), the aperture size is also determined. The facet size of the polygonal mirror can be found by geometry, as well as the overall size of the polygon. Referring to Fig. 3, the radius of the polygon must be large enough to keep the vertices out of the lens aperture during the rotation producing the scan of a line.

Since a gaussian illumination of the aperture is being used, the full aperture diameter must be larger than that computed from equation (2) for a uniformly illuminated lens. A best estimate of satisfactory performance with gaussian illumination was *f*/10 and the polygonal mirror was designed not to truncate this aperture during the scan. The value of R for this condition is 9.7 cm. The location of

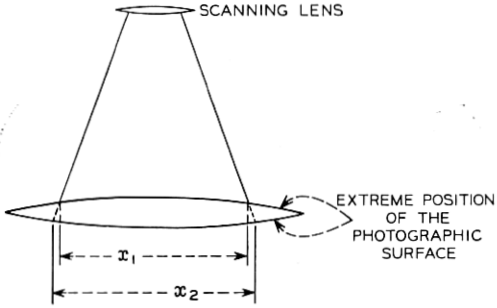

Fig. 2—The effect of photographic plate camber.

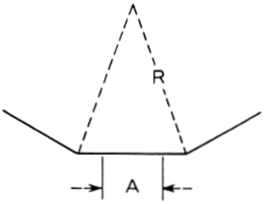

Fig. 3—Polygonal mirror-lens aperture geometry.

the aperture plane of the scanning lens must lie at the approximate location of the mirror facet. To obtain a uniform scanning velocity from constant angular velocity of the polygonal mirror, a $\theta/\tan\theta$ distortion was part of the scanning-lens design; θ is the angle between incident collimated light and the lens axis.

The number of facets on the polygonal mirror determines the ratio between the time available for writing and the unavailable time. Since the field angle of the written line is 45.4°, 22.7° of mirror rotation is spent writing a line. For the decagonal mirror used, 36° of mirror rotation is required to go from the start of one scan to the start of the next scan. Hence, 13.3° of rotation are unavailable. In order to write a complete pattern in 10 minutes, each scan line must be traversed in 18.8 ms; 11.8 ms writing and 7.0 ms waiting for the next facet to come into position. It is during this wait that the photographic plate is advanced one address spacing (7 μm).

IV. THE OPTICAL MODULATOR

The writing beam modulator used is an acoustooptic deflector.[7] The modulator operates by the interaction of the laser beam with a 50-MHz ultrasonic wave in a piece of fused silica. This device deflects approximately 2 percent of the power of the incident laser beam at an angle of 4 mrad to the incident beam when the modulator is energized. Since the modulator is located in a near field region of the laser beam, the two beams emerge from the modulator each nearly collimated but having angular separation. These beams are then passed through a 10-cm focal length lens which transforms the angular divergence into a displacement sufficient for physical separation. The separation is accomplished by a knife edged mirror which has better than a 40-dB discrimination between the beams.

The 2 percent power in the deflected beam provides more than 17-dB on-off ratio and is limited by back reflections and scattering.

However, this is sufficient for the writing-beam modulation. The undeflected beam is used as the coding beam. The modulator has a rise time of less than 200 ns, including the transistor drivers. The transducer is X-cut crystal quartz.

V. MODE-MATCHING OPTICS

A series of lenses are required to transform the output mode of the laser to modes required for the modulator and then to the modes required by the scanning lens. The output of the laser is limited to a TEM_{00} mode by use of an aperture within the laser cavity. The calculation of the positions and focal lengths of the required transforming lenses was done using the method described by H. Kogelnik.[8]

The first transformation is between the laser output and the optical modulator. The modulator requires a 300-μm waist radius in the fused silica. In turn, this mode is transformed to a 55-μm waist located at the knife-edged separation mirror. The writing beam is transformed to approximately a 9-μm waist radius at the object focal plane of the scanning lens and the proper writing spot is produced. The code beam is transformed by a pair of lenses. The first produces a mode having a waist radius of 800 μm, an essentially collimated beam for the 50-cm distance to the code plate. The second lens is a cylindrical lens which produces a 4-μm waist radius in one direction and does not change the 800-μm waist radius in the perpendicular direction. This slit-shaped spot is imaged by the scanning lens to a slit spot on the code plate.

VI. THE CODE PLATE

The code plate is a ruled grating having approximately 13,300 cycles. Each cycle consists of a 7-μm opaque region and a 7-μm clear region. The slit shaped coding beam is focussed in its narrow dimension to best resolve the grating. The long dimension of the beam is aligned to the ruling direction of the grating. In this manner, small defects in the grating, dust specks and pinholes do not significantly affect the code-plate system.

The coding beam will traverse the full-field angle over the scan of a line. In order to collect the coding beam onto a photodetector after it has passed through the code plate, a Fresnel lens is positioned beyond the code plate (see Fig. 1). This lens images the aperture of the scanning lens onto the face of a photomultiplier tube. The sensitivity of this device is required so that the coding beam can be attenuated by approximately 20 dB before it illuminates the scanning lens. If this attenuation is not used, then the scatter from the intense coding beam fogs the photographic plate and reduces the modulation capable of being obtained with the writing beam alone.

The processing and use of the code plate output is described in Part III—The Control System. The alignment of the code plate for production of an accurate scan is described in Part IV—Alignment and Conclusions.

VII. ACKNOWLEDGMENT

The acoustooptic modulator, its driver and gating amplifier were designed and constructed by R. W. Dixon and R. V. Goordman.

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