AN ELECTRON OPTICAL TECHNIQUE FOR LARGE-CAPACITY RANDOM-ACCESS MEMORIES

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INTRODUCTION

Memories of the electron beam recording type have many desirable features for large capacity applications. At the Wescon Conference of 1958,[1] the author proposed a class of electron optical memories of very high storage density under the title, "Information Storage in Microspace."

The intent of the microspace approach was to increase the storage density to a level at which the entire memory surface could be so small that:

1. The memory could be enclosed in a convenient-sized, controlled environment, such as a vacuum chamber, free from dust, stray fields, temperature excursions, and other extraneous influences.
2. The memory surface would not be liable to injury from being rolled or folded upon itself.
3. The mechanical motions could be drastically reduced or eliminated altogether.
4. The difficulty of relocation of the data, which increases monotonically as the memory capacity is increased, could be lessened by organizing the memory in segments with servo-control of the electron beam to and within a given segment.

The desirability of completely eliminating mechanical motion so that rapid random access could be obtained to any part of the memory soon became apparent. However, this goal is unattainable with a single electron lens because of the limitation in field of view of a single lens. One suggestion for getting around this limitation, and thus for increasing the amount of storage surface which can be in focus simultaneously, was made by the author at the Fourth Electron Beam Symposium in 1962.[2] This suggestion was for the creation of a matrix of electron lenses resembling in principle the compound eye of the insect world and thus called a fly's eye lens. In this matrix of lenses, which may be either an electrostatic or electromagnetic array, each lenslet will be capable of keeping that part of the memory surface immediately before it in focus at all times, ready for instant recording or readout.

TYPICAL FLY'S EYE STRUCTURE

A schematic diagram of a cross section of such a device employing electrostatic lenses of the "Einzel" type is shown in Fig. 1. Here the lenslets are arranged in a rectangular array. The inset, at lower right of figure, shows one lenslet of the complete

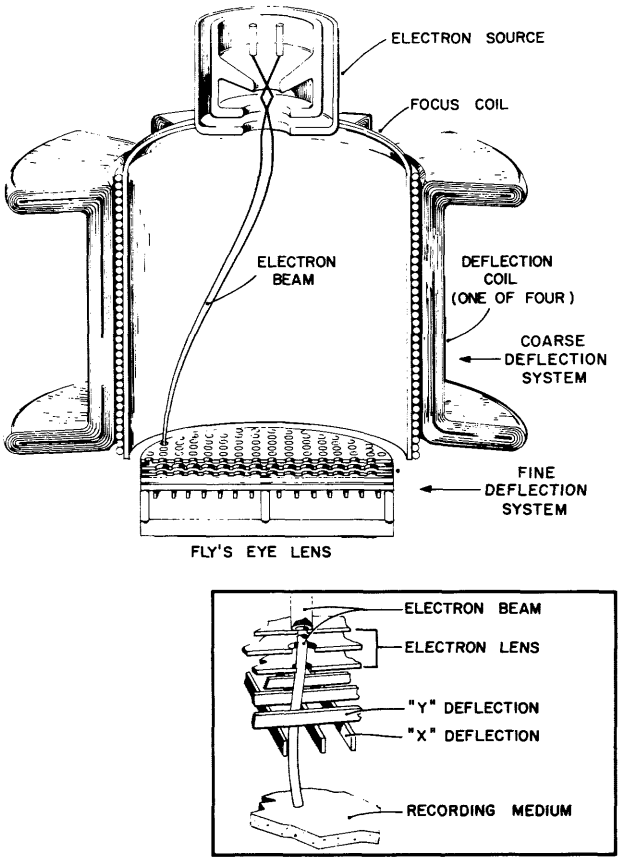

Figure 1. Schematic diagram of microspace concept employing fly's eye lens.

lens in greater detail. It may be seen that the lens is an array of simple Einzel lenses formed as usual by three apertures on a common axis.

All the center apertures of the lenslets are contained in a common metallic plane sheet which is maintained at a potential approaching cathode potential, or at least negative with respect to the electron beam potential. In like manner the outer apertures of all the lenslets are contained in a common metallic plane, for each side respectively, and these outer planes of apertures are at anode potential, which is customarily also the ground potential of the system. Thus for the complete matrix of lenslets three leads are required, one for each plane of apertures. It does not matter that all lenslets are connected, since only that lenslet or lenslets to which an electron beam is directed will be active. Thus if a common electron source is employed with a coarse deflection system as shown in Fig. 1, it can be used as an electrical switch to activate any required lenslet on command.

Immediately following each lenslet a set of X and Y deflection plates, forming a fine deflection system, is shown. From the inset it may be seen that the deflection plates for each row of lenslets form a continuous deflection bar. The other set of deflection plates form a continuous set of bars for the columns of lenslets. Thus, as in the case of the lens plates, a few connecting leads serve to supply voltage to all of the lenslets' deflection plates since it does not matter that a deflection field exists in every lenslet. Only the one lenslet to which the electron beam is addressed is activated. The direction of deflection in adjacent lenslets is reversed but this is of no special consequence for most possible applications.

This fine deflection system is then followed by the recording medium as shown. The precise form of the recording plate depends upon the properties of the medium, which is beyond the scope of the present paper. For purposes of the tests reported here Lippmann-type photographic emulsions have been employed. The above straightforward arrangement has been described in detail because it is the form which has received the most extensive testing and upon which the results reported here were performed. By way of example, a possible variation might contain the focus and deflection functions in the same structures, or the lenslets might be in hexagonal array instead of rectilinear array as shown.

CONSTRUCTION OF A TEST MODEL

As a first test model, it was decided to build a 10 by 10 lens matrix on $\frac{1}{16}''$ centers (which is roughly 1½ millimeters). The complete matrix of 100 lenses was therefore contained in an area of 2.25 square centimeters although the supporting structures extended beyond the lens matrix to a diameter of approximately 5 cm. The central aperture was chosen to be 0.010″ (0.25 mm) diameter and the spacing between planes the same value. The deflection bars were made by simply milling slots in metal plates to form four comb-like structures which could be interdigitated to give the required two sets of deflection plates. A completed assembly is shown in Fig. 2.

EXPERIMENTAL SETUP FOR TEST

The test of the fly's eye unit was conducted in a demountable electron optical bench similar to the bench described by Ruska.[3] The test arrangement is

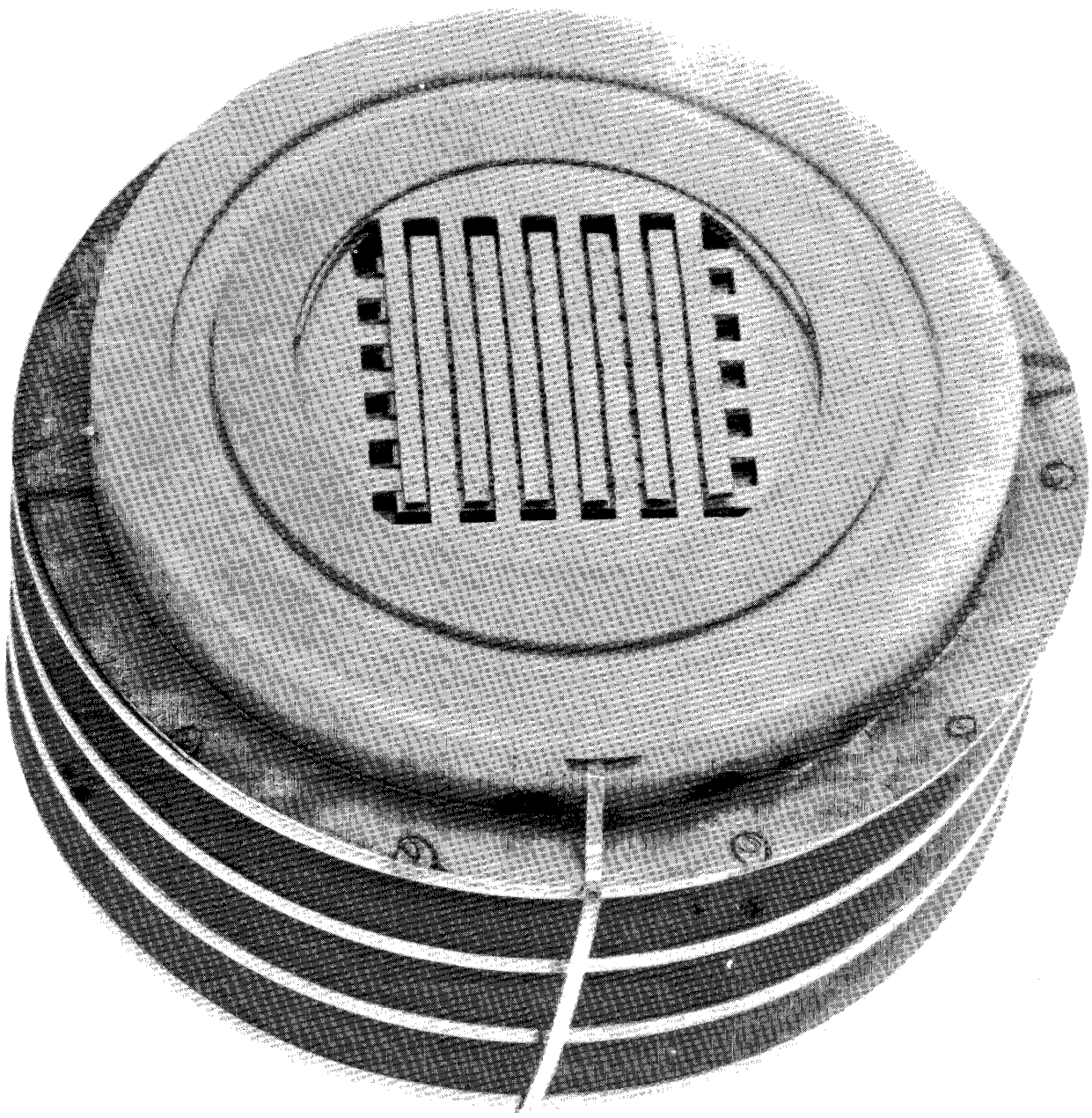

Figure 2. Completed assembly of 10 by 10 matrix fly's eye lens.

shown schematically in Fig. 3. Only the top section of the equipment is illustrated. The electron source and condenser lens assembly (not shown) were respectively a standard hairpin filament source and an electrostatic condenser lens described previously by the author.[4] This source size has been found to be approximately 75 microns in diameter. The image and object distances were set to give a demagnification of 60 times. A fine-grain (vapor reacted) phosphor screen* shown in Fig. 3 is placed at the focal position of the fly's eye structure seen immediately below the fluorescent screen. Above the screen is a light microscope objective contained in the vacuum. The objective can be focused from outside by means of the bevel gear train. The light microscope viewing system is completed by an eyepiece external to the

* Vapor reacted screen obtained from Liberty Mirror Division of Libbey-Owens-Ford.

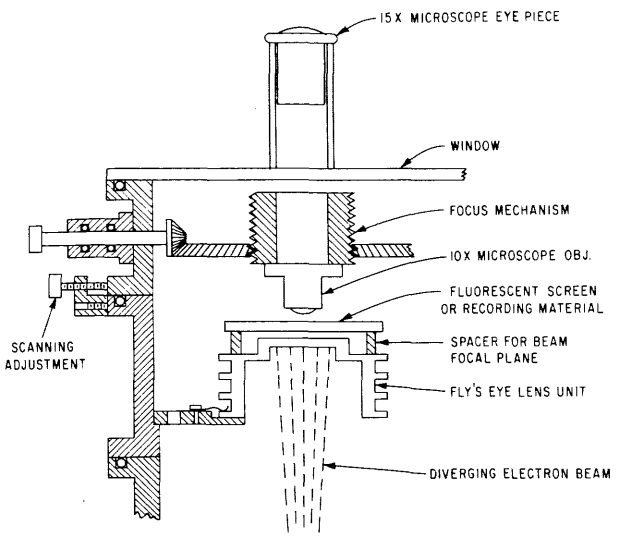

Figure 3. Schematic of test arrangement for fly's eye lens evaluation.

vacuum window. Viewing magnification could be varied from 50× to 400× by exchanging objectives and eyepieces.

A photograph of the test setup, on the electron optical bench, is given in Fig. 4. In the vertical column of electron optical components, the electrons proceed from bottom to top. The column is 4″ in diameter (approximately 100 mm) and is connected to the vacuum system by a metal cone seen to the lower right of the column. This cone is welded to one section of the column and serves also as the mechanical support for the column. Just below the cone may be seen the insulator for the electron source described in Ref. 4. The section immediately above the cone houses the electrostatic condenser lens of Ref. 4. Centering of the elements is accomplished by sliding action of the "O" ring seals between sections and is controlled by means of the external collars and thumb screws which may be seen in the photograph at the junction of some adjacent sections. The next three short sections house the fly's eye lens. The top of these three sections is made of lucite plastic to aid in beam current measurement and introduction of the focus voltage to the lens. The middle section contains six insulators, four of which are used to introduce the deflection voltages, one for providing ground potential to the top lens plate and the last not used since the bottom lens plate is fastened to the lowest of the three sections and thus provided with adequate ground connection and mechanical support. The fluorescent screen or photographic plate is held at the correct focal plane for the fly's eye lens by a simple annular, ceramic, ring spacer placed to rest on the outer edge of the lens. The fluorescent screen has a conducting coating and is connected through the plastic section to a lead for either simple ground connection or connection to a beam current meter with appropriate positive bias to collect secondary electrons and obtain a true reading. The photographic plate is exchanged for the fluorescent screen by breaking vacuum and lifting off the top two sections. For light sensitive materials this operation is conducted with the aid of a red cellophane filter in a flashlight. The photographic plate is kept from moving during exposure by a large-diameter, weak coil spring pressing down on it. Obviously, the system must maintain

Figure 4. Photograph of test arrangement for fly's eye lens evaluation on electron optical bench.

alignment and focus through this vacuum cycle. The top two sections contain the objective lens assembly of the viewing microscope with its planetary gear system for external focus control obtained by the knob seen on the right. The top section allows space for this focus motion. The eyepiece of the viewing microscope is external to the vacuum system and may be seen at the top of the column. This arrangement places the vacuum chamber window between the objective and the eyepiece where it introduces negligible aberration. To the left of the column one may see the polyethylene high voltage leads which supply condenser lens and fly's eye lens focus voltages. Their respective high-voltage plastic bushings are on the back side of this view and therefore cannot be seen. These bushings are completely enclosed for safety reasons, as are the leads to the electron source seen at the bottom of the column.

TEST OF THE 10 BY 10 MATRIX

For the first test, the light microscope was removed after focusing and the electron source was made to flood all of the lenslets with a 4-keV beam by causing the beam to cross over close to the condenser lens. The simultaneous focusing action of the lenslets with grounded deflection plates was observed on the fluorescent screen. The fluorescent screen image was recorded by 35mm photography, as shown in the image sequence in Fig. 5. Subsequently, the light microscope was reinstalled and the fine deflection system of the fly's eye was connected to the plates of a type 536 Tektronix oscilloscope, which gave a maximum potential of 160 volts in one direction and 80 volts in the other. The plates also contained a DC bias of approximately 80 volts. A simple sawtooth pattern was observed on the fluorescent screen by use of a 16-mm 0.25 NA objective. A photographic plate was then used in place of the fluorescent screen by opening the vacuum system and then exposing the plate without the possibility of reexamining the focus. The sawtooth trace approached 1.5 microns at the narrowest part which is consistent with a demagnification of about 60:1 and a source size of about 75 microns and gave encouragement to attempt image recording through the lens.

IMPROVED TEST SETUP

Before making test recordings the setup shown in Fig. 4 was added to and improved in the following

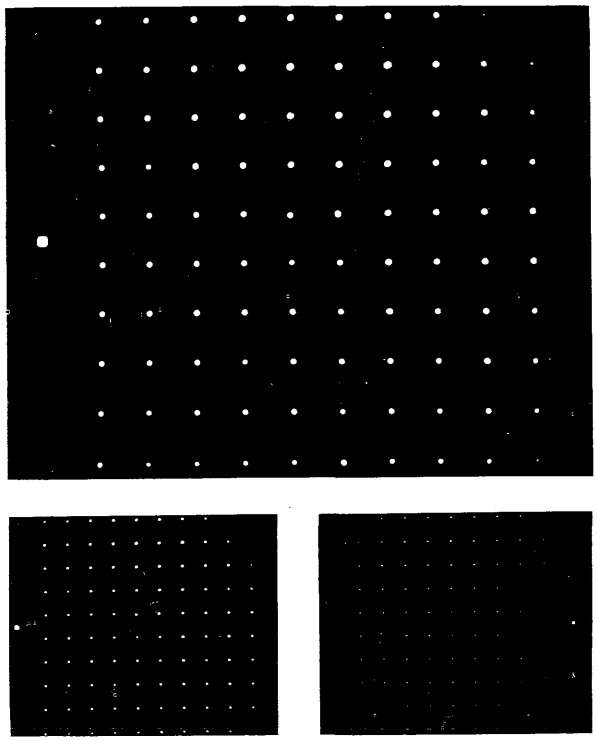

Figure 5. Focal sequence of 10 by 10 fly's eye lens. *Top:* .625 × .625 fly's eye electron beam pattern; beam entered corner lenslets at an angle. *Bottom:* Two stages of focus through all lenslets.

manner. A stator type television focus coil* was added between the condenser lens and the fly's eye unit using a brass tube through the center of the coil to keep it outside the vacuum chamber. The brass tube had flanges connected to each end by threaded joint and "O" ring seal to make it compatible with the rest of the sections in the electron optical bench column. While this deflection unit permitted the use of areas of the fly's eye away from center, it could not adequately direct the beam to the outermost lenslets because the angle of the beam to the lens normal increased with deflection. In the latest version, described below, this limitation is removed by employing double deflection so that a second set of coils straightens the beam back to the lens normal just before it reaches the required lenslet opening. The simple deflection control from the 536 oscilloscope was replaced by control from an image orthicon chain.† Signals are fed, through appropriate video amplifiers, from the chain to the fine deflection bars and the grid of the electron source. Deflection

* Celco Type AY 521–5600 (Constantine Engineering Laboratories Co.).

† General Electric Model URV–200.

levels available were ±400 volts and grid swing was up to −20 volts coupled to the gun with a .02 Mfd, 6 kv capacitor. After the first images of a test chart, shown in Fig. 6, were recorded the fly's eye unit was mounted in a more convenient electron optical bench section designed specifically for holding it, and a plate holder was added with a linear motion feed-through so that the fluorescent screen and photographic plate could be interchanged over the fly's eye unit without breaking vacuum. It was still necessary to break vacuum to place the photographic plate into or out of the system however. An adjustable aperture similar to the one described in Ref. 4 was installed between the source and condenser lens and a simple mechanical shutter with a Faraday cup on its extremity was installed to control exposure and measure total beam current. Finally the hairpin filament of the electron source was given a small pointed end after the method of Hibi [5] to decrease the source size without loss of brightness. For visual focusing the current at the fluorescent screen was raised to 10^{-7} amperes or higher, but for photography the current had to be reduced below 10^{-9} amperes to give a convenient time of 1 to 10 seconds for mechanical exposure. It is not possible to determine by fluorescent screen viewing whether the resolution suffers at higher beam current but no deterioration is expected. This item will be tested when single trace photographic control becomes available.

PHOTOGRAPHIC RESULTS

Photographic emulsions of Lippmann-type were used to test the performance of the fly's eye lens. At

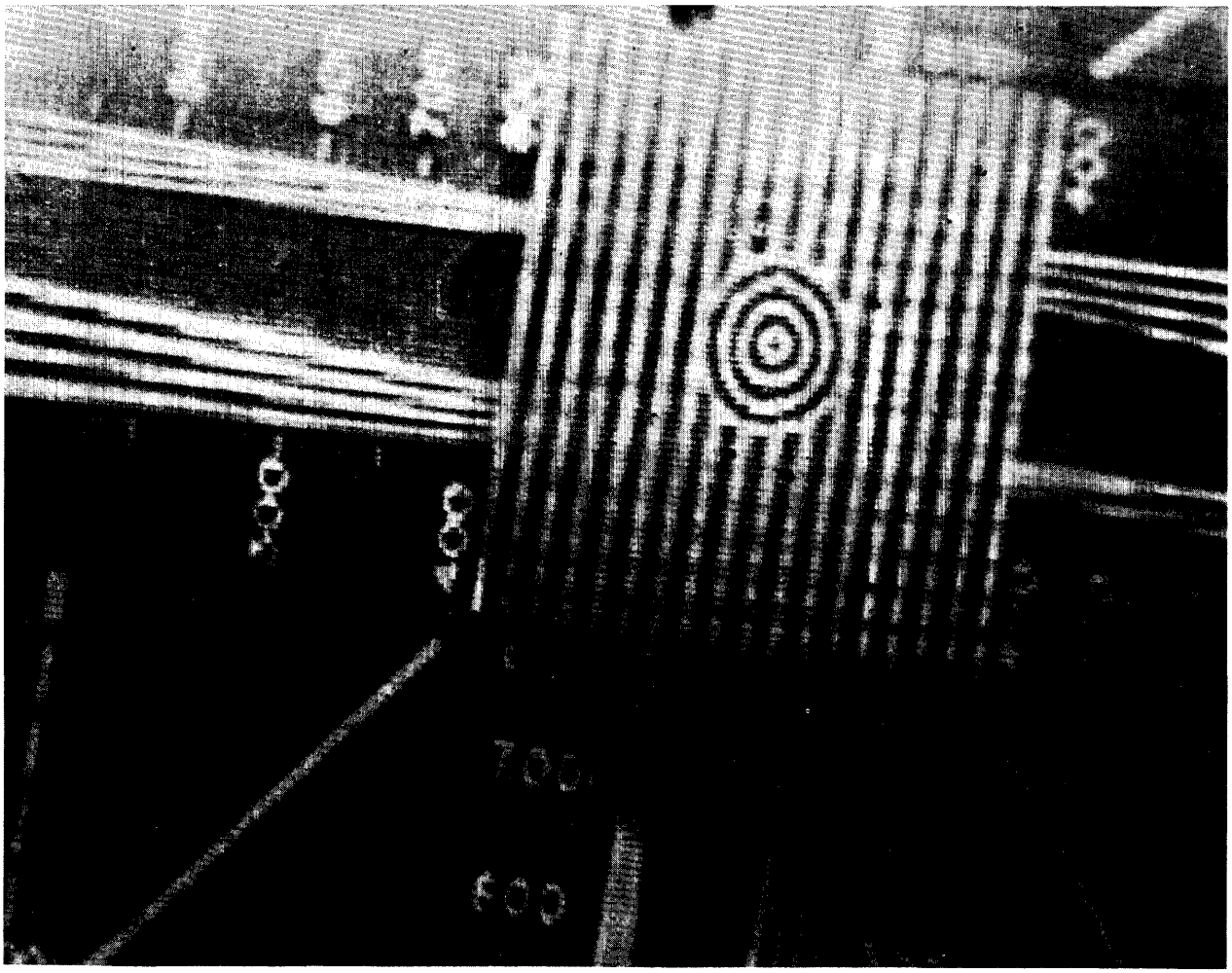

Figure 6. Portion of RETMA resolution chart by scanning action of one lenslet recorded on photographic film. Magnification marker—100 microns.

first Kodak high-resolution plates were used but the 4-kV beam energy was insufficient to reach the silver halide grains so that recordings were essentially due to changes made in the surface of the gelatin. This difficulty was overcome by making emulsion coatings of low gelatin content according to the method described by Salpeter and Bachmann.[6] Later on Eastman Kodak produced some experimental Lippmann-type emulsion of low gelatin content and grain diameters around 50 mμ, which was more convenient to use. A good description of Lippmann emulsion is given by Mees and James.[7] This emulsion can be spread in thin layers after the method of Hamilton and Brady [8] and mounted on a glass slide or electron microscope specimen grid. It has been supplied to us through courtesy of the Kodak Company on a purely experimental basis and no assurance can be given regarding future availability. The pictures shown here were made with this emulsion on tin-oxide-coated microscope slides. Development was for one minute in D-19 developer. Hamilton and Brady suggest a developer containing ascorbic acid for best resolution, but it is less stable and not required at the present resolution level.

The image shown in the photomicrograph of Fig. 6 was produced by scanning action by one lenslet of the 10 by 10 matrix of lenslets. The image is of the RETMA resolution chart #1956, the photomicrograph was made with a 10× objective. Figure 7 is from the same recording as Fig. 6 but taken with a

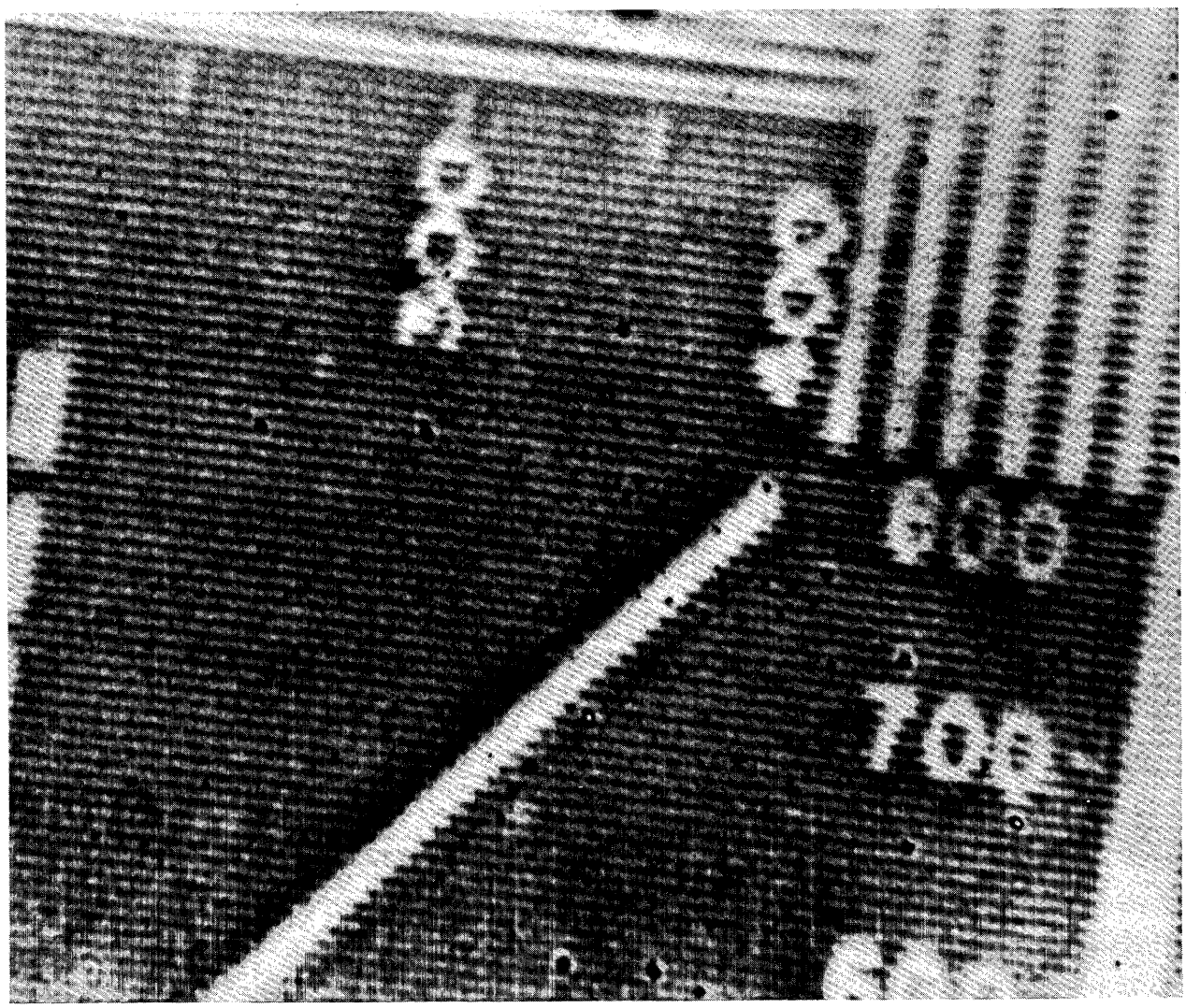

Figure 7. Higher-resolution microphotograph of recording shown in Fig. 6. Magnification marker—10 microns.

20× objective. For a restricted field of view, it shows the individual scan lines in better detail. Even Fig. 6 does not cover the entire picture. It is unfortunate that the optical microscope cannot both resolve the scan lines and cover the field of view of the entire recording although it may display either one by itself when the proper objective is used. At the border of Fig. 7 is a magnification scale representing 10-micron spacing between centers of adjacent lines. This scale was produced by photographing a 10-micron Bausch & Lomb scale immediately after photographing the fly's eye image and with the same setting of the microscope except that dark field illumination was used to make the scale lines more distinct but, of course, reversing them from black to white. The Leitz ortholux microscope and 35mm orthomat camera were used to take the pictures. In both Figs. 6 and 7 the path of the electron beam on the printed page is black. We have a further check of their identity because the test chart bars and numbers appeared black on the fluorescent screen prior to recording and therefore must be opposite to the electron beam, which glows brightly on the fluorescent screen.

For these pictures electron optical demagnification was approximately 20:1, the object and image distances being 10″ and 0.5″ respectively. Assuming negligible lens aberration a source size of 20 microns is indicated which is reasonable. Beam currents of up to 1 microampere were observed on the fluorescent screen but beam current had to be reduced to 5×10^{-10} amperes to give a reasonable exposure time for the Kodak experimental emulsions and mechanical beam shutter used. Again, the beam voltage was 4 kV and the deflection voltage was ±400 V to give a deflection of $\frac{1}{16}$″ to match the lens matrix spacing.

PRODUCTION OF A 32 BY 32 MATRIX LENS

After the initial test of the 10 by 10 matrix lens and during the time of the later tests, an improved version of the fly's eye structure was produced as seen in Fig. 8. Its chief differences were improved tolerances in centering the plates during assembly, production of deflection bars which were anchored at both ends and a 10-fold increase in the number of lenslets to a 32 by 32 matrix on $\frac{1}{32}$″ centers (approximately ¾ mm). This lens has given the improved pictures shown in Figs. 9 and 10, which contain lines less than 1 micron on two micron centers. Figure 9 shows simulated digital data being scanned by four neighboring lenses simultaneously. The apparent lack of linearity is chiefly due to the signal source. This becomes apparent when it is recalled that adjacent lenses give mirror images. The distortions are seen to be reproduced identically by each lens. Figure 10 is included to give some idea of gray scale response and shortness of exposure. (Figure 10 was taken "live" not from a photograph. Also, an extra photographic reversal was introduced to avoid a negative for the final print.) The improved test equipment shown in Fig. 11 has been provided and a small electron microscope has been constructed to permit focusing the electron beam at submicron dimensions. For these proposed tests the demagnification may be increased to 50:1. If the lenses were mechanically perfect, the aberration limit would be expected to be 0.03 microns. Photographic film has been shown by Salpeter and Bachmann [6] to be capable of an average grain size of 0.05 microns. Thus a resolution of 4000 line pairs per millimeter is a worthwhile goal to strive for, since we have emulsion capable of recording at this level.

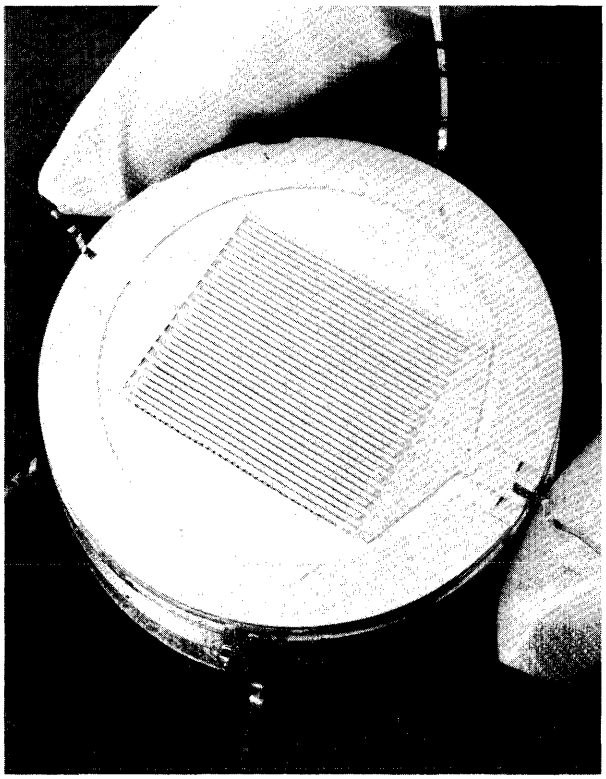

Figure 8. Completed assembly of 32 by 32 matrix fly's eye lens.

IMPLICATION OF RESULTS

The full resolution of the available 480 lines of the television signal indicates better than 2×10^5 clearly resolved spots in the field of view of each of the 10^3 lenses. This result is most encouraging, the principal problems ahead for this device now appear to be ones of quality control since it has been shown that the lens and deflection system can be scaled down according to scaling laws. In the process of scaling down, the bits resolved per lens and the current density at the recording plane are constant while the bit density decreases as the square of the scale factor and the device size decreases by a factor between the square and the cube of the scale factor. (Obviously, this process cannot be continued

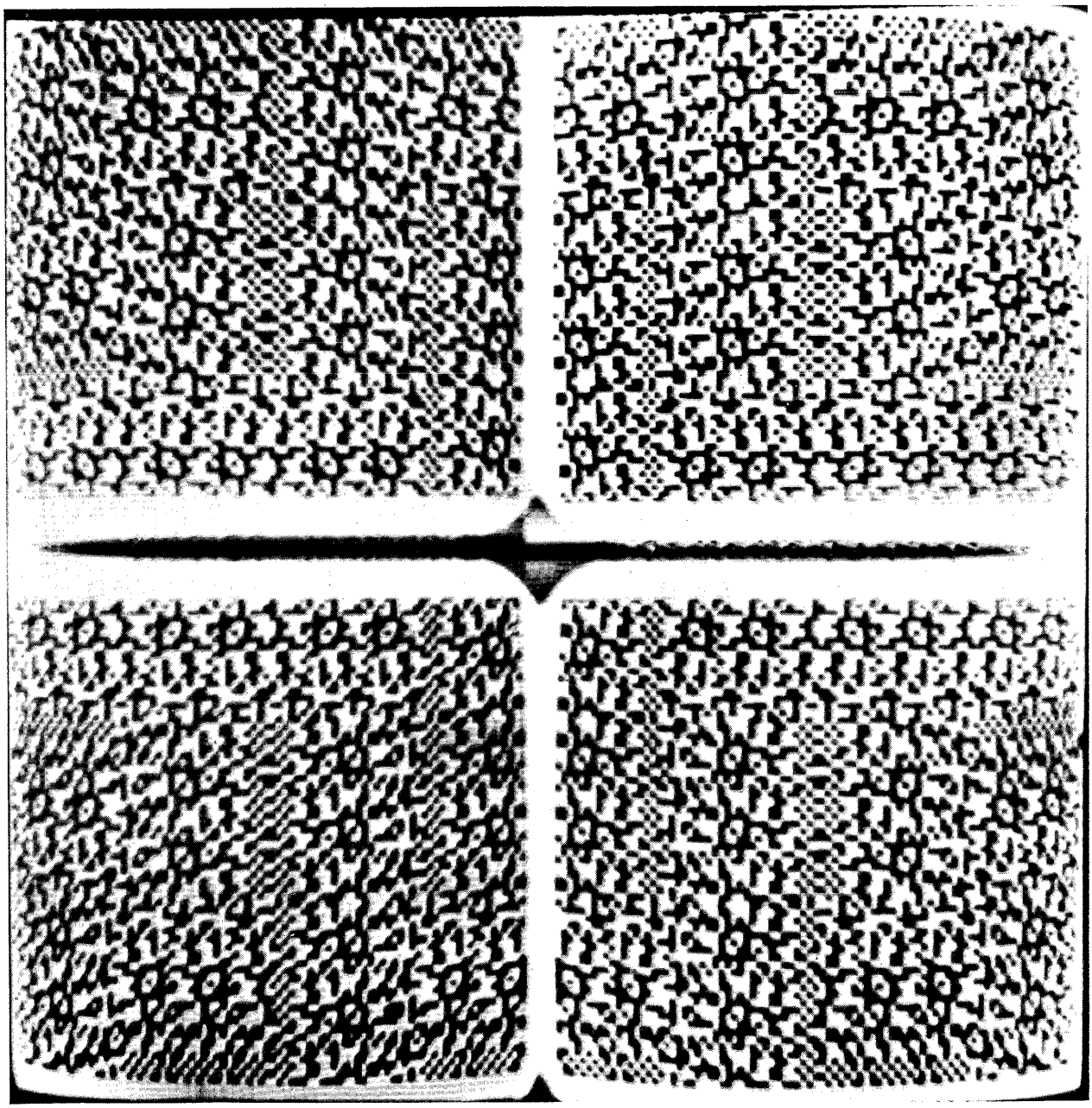

Figure 9. Image of simulated digital data from four neighboring lenslets of 32 by 32 matrix, illuminated by a single large-diameter beam. Data squares are 10 microns high while scan lines are less than one micron on two micron centers. Resolution is limited by the optical read-back system rather than the recording.

Figure 10. Portion of live image recording on photographic film. Scanning beam less than 1 micron on 2-micron centers.

indefinitely without increasing current density since one would eventually reach a limitation due to the statistical inadequacy of the electron beam, because while current density is maintained at the same level, ampere seconds per spot is reduced. We are well removed from that limitation in present considerations, however.) Thus each of the 1000 small lenses should ultimately be capable of recording the same number of bits per field of view as a large lens which certainly approaches 10^8 bits. The advantage is that 1000 of these single tube memories are contained in one small device with a small number of input leads.

In summary, we have described a novel electron optical element which permits the entire memory plane to be in focus at one time. The current density at the recording plane is maintained and the memory plate size is reduced by the square of the scale factor. A packing density of 10^8 bits per square inch has already been demonstrated with 1 micron beam

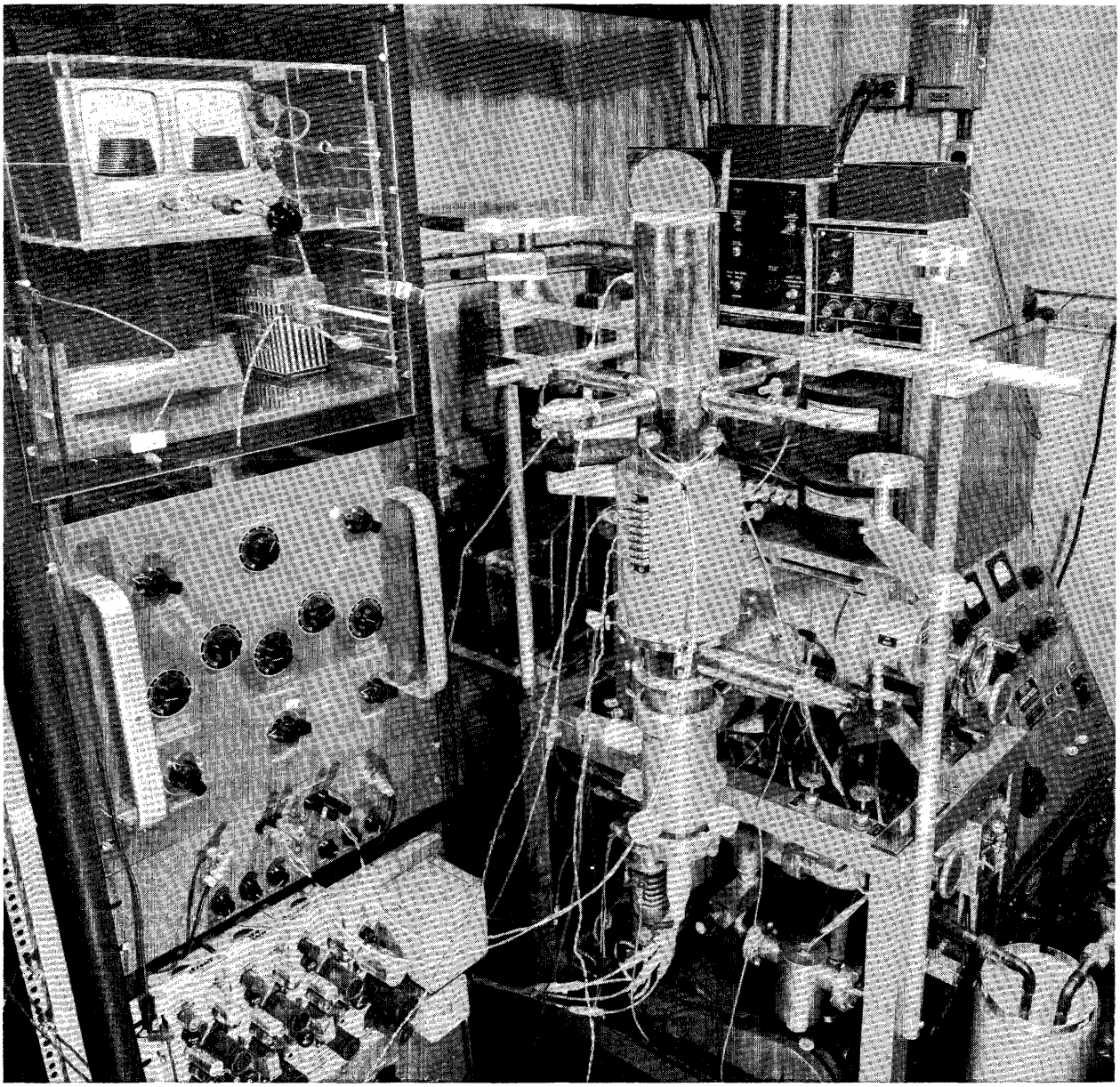

Figure 11. Improved test equipment for continued evaluation of 32 by 32 lens in submicron recording dimensions. Small electron microscope added at top for focusing electron image.

diameter. The next extension of performance will require an electron microscope to judge focus of the beam and to display the recording.

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