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U.S. DEPARTMENT OF COMMERCE / National Bureau of Standards

Semiconductor Measurement Technology:

A Laser Scanner for Semiconductor Devices

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A Laser Scanner for Semiconductor Devices

by

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Abstract: This is a construction guide and operators manual for a laser scanner built for semiconductor device studies. A very brief discussion of the theory of operation of the scanner is given. The scanner's operation from a systems point of view is described in detail with emphasis on block diagrams. The scanner is described from a hardware point of view with a detailed description of the function of the various controls on the electronic equipment that was built for the laser scanner. A quick guide for the use of the scanner is given so that a person unfamiliar with the instrument can use it effectively. Specifications relating to the scanner's data gathering ability are also given. Mechanical drawings and circuit schematics are given to enable others to build a similar scanner. The optics and their alignment are discussed. Various display modes including color are discussed to enhance operator viewing.

Key Words: Electronic reliability, electronics; laser scanner; measurement method; mixer; optics; pre-amplifier; radio receiver; semiconductor device studies.

1. INTRODUCTION - PURPOSE OF THE LASER SCANNER

The National Bureau of Standards laser scanner is a versatile apparatus which can be used to study photo-responsive materials and devices on a point by point basis. The scanner is intended for specimens that have a physical size such that they can be viewed under a typical optical microscope and would require magnifications that are typically achieved by such microscopes. The scanning system, by its very nature, produces an output which is an electrical signal that can be displayed in real time on a cathode ray tube (CRT) or which might be processed electronically in some other manner. Specifically, the National Bureau of Standards laser scanner was assembled to determine the usefulness and versatility of such an approach for studying semiconductor devices such as transistors and integrated circuits, and the materials from which these devices were made. The laser scanner is an apparatus that is able to nondestructively map photosensitive semiconductor devices and materials by scanning them with low power lasers. In general, the specimen being scanned is its own detector. The scanning operation is intended to reveal information which can be used to gain insight as to how well a particular semiconductor device is working on a point by point basis. The scanner can be used to locate weak points and stress points in functioning devices, as well as failure locations on failed devices. The scanner might also be valuable for checking semiconductor materials for quality (1).

The scanner, like the scanning electron microscope (SEM), requires interpretation of the displays generated. Unlike the SEM, the scanner is completely non-destructive to the device being studied. Several aspects of the usefulness of the scanner described in this report have been reported in the literature. These include mapping high and low frequency signal characteristics of transistors, spatially pin-pointing nonuniformities in thermal characteristics and linearity characteristics of transistors, revealing logic states in MOS and bipolar integrated circuits, and changing the logical state of elements in an IC (2,3,4,5,6). Of course, an important requirement for optical scanning is that the active areas in the device must be accessible by light and not totally covered by metal. The trend, however, in modern device design is toward interdigitated structures and polysilicon gates, so it is easier to obtain scanning results now than it has been previously. In certain types of devices, it is also possible to scan the device from the back side, thus eliminating any problem connected with top metal coverage.

In interpreting the display, the total operation of the specimen must be considered. For example, the information gathered by scanning an integrated circuit is obtained by monitoring changes in power supply current to the device, and so all the effects of photogenerating a current in a particular transistor within the IC may need to be fully taken into account. In scanning the transistor, only a small increase in collector current and thus power supply current would be produced if the device were electrically isolated. However, if the scanned transistor serves as a signal source for others, then the supply bus signal will be a composite of the various device currents. In some cases, the effect of scanning a portion of a device is to reduce the bus quiescent current, and this produces a darkened region on the display screen. While these considerations are important in explaining apparent photoresponse signal strength and polarity, only the elements that give a photoresponse will show in the display; so the situation is not as complicated as it may seem. Furthermore, specimens having a large number of transistors are usually digital and small changes in current passing through a given transistor influence few others. Even if the scanned IC were linear rather than digital, some degree of response isolation may be achieved automatically. For example, many linear circuits contain negative feedback loops, and these may compensate for perturbations introduced inside the loops.

In hopes that semiconductor device manufacturers and users would find it desirable to have a laser scanner similar to the one developed at the Bureau, this publication has been prepared to serve as both a construction guide and an operator's manual. Highlights in this publication include mechanical and electronic schematics, examples of uses, and a guide to the operation of the scanner.

2. OPERATING MECHANISM AT THE DEVICE LEVEL

A moving light spot, generated by a mechanically deflected laser beam, has the effect of generating current carriers in the semiconductor material. In the simplest case, this can cause a current in an unbiased junction if the light spot falls sufficiently close to the junction. This current can be measured in an external circuit connected to the device being scanned. As the light spot is swept across the device being scanned, the amplitude of this current will vary as the composition of the semiconductor device changes. This current variation is the information that is used to present a photoresponse map of the device being scanned. The current variations are simply amplified and fed to a cathode ray display which is driven in synchronism with the laser scan. The information is obtained by interpreting the map produced.

The system works equally well for mapping reversed-biased junctions. In this case the light spot, in generating carriers, causes the reverse current to increase. This change of current can be produced in the same manner as for the non-biased junction. If a transistor biased in the active mode is observed using the laser scanner, a change in base-collector junction current may be amplified by the transistor being scanned to give an enhanced photoresponse map.

Another category of studies that can lend itself to observation on the scanner is that of resistivity. In particular, a resistor in an integrated circuit can show a photoresponse when the circuit is scanned. Again, the light spot creates carriers in the semiconductor material, but in this case the semiconductor becomes more conductive and the current passing through the resistor increases. For the resistor to be detected on a photoresponse map of the device being scanned, the resistor must be carrying a current. The scanner can be used to tell how uniform a resistive area is. If the resistor is in the base circuit of a transistor biased in its active region, this current can be amplified to give an enhanced photoresponse.

In FET transistors and integrated circuits the light spot can cause an increase in the current in the channel. With proper interpretation one can tell which transistors in MOS arrays are on and which are off.

3. PRINCIPLES OF OPERATION

3.1 Optical and Mechanical Operation

The laser scanner incorporates two low-power, continuous wave helium-neon lasers. One of the lasers operates at a wavelength of 0.633 μm in the visible portion of the spectrum, and the other at a wavelength of 1.15 μm in the near infrared. A movable slide in the optical paths of the lasers allows the user to select which of the lasers is to be used for a particular experiment. The chosen laser is sequentially reflected from two nodding scanning mirrors which oscillate in orthogonal directions. The moving light spot forms a raster on the specimen upon being directed through the camera tube of an optical microscope (see Appendix A for a description of the microscope). The specimen is electrically connected to a cathode ray display which is deflected in synchronism with the scanning mirrors.

Let us examine the system in more detail. Figure 1 is a pictorial diagram of the light and signal paths of the dual-laser scanner. The beam from the 1.15 μm laser is deflected from M_1 through a half wave plate onto M_2. The half wave plate is used to rotate the polarization angle of the 1.15 μm radiation to maximize the intensity of the radiation at the specimen and, more importantly, at the reflected light photodiode (see Appendix A). The mirrors M_1 and M_2 fold the optical path to make the scanner more compact and rugged. Mirror M_2 directs the 1.15 μm laser beam toward the first deflection mirror labeled V. The beam of the other laser, which operates at 0.633 μm, passes through a polarizer-analyzer, and is deflected from mirror M_4 onto mirror M_3. The analyzer can be used to attenuate the beam when desired. Mirrors M_4 and M_3 are located on a movable slide. When this slide is moved to the right, the beam is reflected from M_3 onto the first deflection mirror V. When the slide is in this position the beam from the 1.15 μm laser is blocked. When the slide is moved to the left, the 1.15 μm radiation is allowed to fail on deflection mirror V and mirrors M_4 and M_3 no longer direct the 0.633 beam onto V. The first deflection mirror V generates the vertical component of the scanning raster. This mirror is a commercially available galvanometer device. This mirror is driven with a triangle waveform through a suitable power amplifier. After the light leaves the vertical deflection mirror V it passes through a lens system designated L_1 which has the effect of focusing the vertical deflection from V onto the horizontal deflection mirror H(7,8) (see Appendix B for a complete description of the lens system represented by L_1). Refocusing the vertical deflection onto mirror H allows H to be small so that faster scanning rates can be used. Mirror H is located at the exit-pupil point of the microscope camera tube. The beam diverges from the horizontal mirror H to form the scanning raster. The raster is focused onto the specimen by the microscope optics. The scan raster can cover all of the field of view that can be seen with the eye when the microscope is used in its usual manner. Additional details of the mechanical construction are given in Appendix C.

The laser scanner incorporates a reflected light circuit to enable one to obtain a map of the topography of the specimen being scanned. This circuit makes use of a half-silvered mirror that is built into the microscope for vertical illumination purposes when the microscope is used in a normal manner. Some of the laser light that is reflected from the specimen as it is scanned is collected by the microscope's objective and subsequently reflected from the half-silvered mirror in the microscope. This light passes out of the microscope through the vertical illuminator. In order that the microscope could retain its vertical illumination capability, a second half-silvered mirror (not shown in figure 1) was placed in the vertical illuminator tube (see figure C 17 in Appendix C) to direct the reflected light out of the tube and through a lens L_2 and onto a germanium photodiode. The second half-silvered mirror makes it possible to use either the vertical illumination or the reflected light circuit without changing any parts. The lens L_2 focuses the raster of the reflected light to a point on the photodiode. Refocusing to a point is necessary so that irregularities in the photodiode do not distort the electrical signal obtained from that device when the scanning mirrors V and H are driven to fairly high excursions. A germanium photodiode was chosen over a silicon photodiode because the germanium responds to both the 1.15 μm laser and the 0.633 μm laser.

The photocell provides an electrical signal which can be used to obtain a spatial map of the *reflectance* of the specimen being scanned by the laser radiation. Another electrical signal can be obtained from the specimen at the same time, and this signal is extracted by simple electrical connections to the device being scanned. This is the *photoresponse* signal, and it can be used to display spatially the electrical response of the specimen to the laser radiation. This photoresponse signal is generally of greater importance in studying semiconductor devices than the reflected light signal, the reflected light signal being mainly used to identify areas on the specimen that give a photoresponse signal. Both the response signal and the reflected light signal are generated at the same time and are thus synchronized.

3.2 Electrical Operation

Electrical signals generated within the specimen as a result of the laser scanning the device, as well as the electrical signal developed by the reflected light photodiode, are amplified and modulate the electron beam of a cathode ray display. The electron beam of the display is deflected horizontally and vertically at the same rates, and in synchronism to, the deflection of the scanning mirrors. A point-to-point correspondence is thus established between the position of the laser spot on the specimen and the position of the electron beam on the display. As the light spot and the electron beam move, the electrical signals from the device and/or reflected-light photodiode, in modulating the electron beam, produce a picture of the response of the specimen on the display screen.

Figure 2 is a block diagram showing the important elements in the electrical section of the system. The *mixer* is the heart of the electrical system. Its signal processing capabilities include signal amplification from up to three sources, addition and subtraction of these signals (mixing), and superimposing the signals onto the vertical deflection waveform driving the display for the vertical deflection type presentation. The mixer allows signals from the specimen and the reflected light photodiode to be mixed in any desired proportions so that a display of the specimen's photoresponse, for example, can be superimposed on a topological display generated by the photodiode. Any signal, or combination of signals from the specimen can be mixed with the deflection waveform that is used for vertical deflection of the electron beam on the display screen. This is a display technique which provides a picture which appears to have a three-dimensional quality. An advantage of this presentation mode is that it allows quantification of the specimen's photoresponse, since the deflection of the spot on the cathode ray tube display, as compared to a change in spot intensity, can more easily be measured. With the mixer, either the conventional spot intensity modulation, or the vertical deflection modulation, or both, can be used. The mixer provides separate outputs for each of the three channels, and each channel has a voltage gain of up to 50. These outputs can be used for separate processing of the signals derived from the specimen and the reflected light circuits. For example, when a color display is used instead of a monochromatic display (see Appendix D for details) different signals from the device under investigation can be displayed at the same time without losing their identity of origin. Even with the monocromatic display, two of these signals can be separated by using intensity modulation for one signal, and vertical modulation for the other. The mixer has provisions for specimen bias, so that a separate power supply for the specimen is often not needed; however the pre-amplifier (shown in figure 4) has the same provision and is usually used for this purpose. If the specimen signal is very strong the pre-amplifier is not needed and the specimen can be connected directly to the mixer. The schematic diagrams for both the mixer and the pre-amplifier are included in Appendix E along with a more detailed description of the internal circuitry.

The pre-amplifier has two channels which allow monitoring of two different signals that might be generated by the specimen. For example, if the specimen requires two power supplies, variations in both of these supplies can be displayed at the same time. The pre-amplifier has a 0 to 20 V power supply and a 0 to -20 V supply for specimen excitation. There is also a selection of load resistors for each supply. The pre-amplifier has a variable-cutoff high-pass filter which can be used when the specimen is noisy or has a tendency to drift. All of the circuits in both the mixer and pre-amplifier are dc coupled so that slow scanning rates can be used when the specimen requires a long recovery time from the scanning light spot. One of the channels in the pre-amplifier is a special FET amplifier circuit with no loop feedback. This circuit features very fast recovery from transients and severe overload conditions. This feature allows an accurate observation of weak signals when strong ones are present.

The reflected light amplifier is a very simple one which amplifies the signal developed by the reflected light photodiode. The circuit for this amplifier is given in Appendix E.

Two signal generators are used for the laser scanner. One generator, designated *horizontal signal generator* in figure 2, provides both a square wave and a sine wave. It is used at frequencies between 10 Hz and 1.2 kHz. This generator determines the horizontal sweep rate. The other generator, designated *vertical signal generator,* provides both a square wave and a triangle wave, and is used at frequencies between 0.01 Hz and 100 Hz for the frame rate. The square waves of both generators provide the blanking signals, and are fed into the mixer where a composite blanking signal is developed. This composite signal is then fed to the blanking input on the display. The sinusoidal waveform from the horizontal generator is fed directly to the horizontal deflection amplifier in the display. This waveform is also fed to the horizontal scanning mirror through an attenuator which serves as a picture magnifier, and thence to the scan power amplifier which drives the mirror galvanometer assembly. Operation of the magnifier will be discussed in section 4.3. The triangular waveform from the vertical generator is fed to the vertical deflection amplifier in the display; however, before it goes to the display, it first goes through the mixer where specimen signals can be added to the vertical deflection as discussed earlier. The composite signal, consisting of the triangular waveform, and the specimen modulation signal if any, is then fed to the vertical deflection amplifier in the display. The triangular waveform from this generator is also fed to the scanning mirror through a second channel of the attenuator and its scan power amplifier.

The scanning mirrors have a resonant frequency of approximately 1 kHz and do not respond to frequencies much higher. Furthermore, there is a substantial phase shift between the electrical signal driving the mirror and the actual mirror movement at even 100 Hz. It is desirable to use the fastest scanning rates possible for most specimens, simply for viewing ease. If operation at the resonant frequency were used, then obviously some kind of phase shift network would be needed to cause the mirror to move in step with the spot on the cathode ray display. A convenient solution to this problem has been found, and it is to operate the mirror slightly above resonance so as to cause a 180 degree phase shift between the electrical driving signal and the movement of the mirror. Maximum spatial linearity of the presentation is achieved either with an in-phase, or a completely out-of-phase relationship. The picture is reversed by operating at 180 degrees out of phase, however, the picture is linear, and the picture can be restored to its proper perspective by simply interchanging the leads to the scanning mirror. The 180 deg. point can be found by scanning anything that has regularly spaced elements or markings, and using the reflected light circuit to tune the horizontal frequency for a linear picture. The horizontal sweep frequency is about 1.2 kHz, for the scanning mirrors used, when the scanner is operated under these conditions. The galvanometer responds only to the fundamental frequency when driven at resonance, and so the horizontal generator need only furnish a simple sinusoidal signal. A 3-or 4-Hz frame rate usually yields adequate definition with the 1.2 kHz sweep rate. This combination gives a 300 to 400 line scan. A triangular waveform can be used for the vertical scan because the vertical deflection galvanometer can follow this waveform at the rather slow frame frequencies. Much slower scan rates must be used if the specimen cannot recover quickly from the photo-generated signal. For these situations both the horizontal and vertical frequencies are dropped by one or two orders of magnitude. The vernier frequency adjustment on the horizontal generator is usually not disturbed because of the rather critical adjustment needed for the 180 deg. phase shift at 1.2 kHz. Unfortunately, when the scanning mirror is switched out of its 180 deg. phase shift mode to a lower frequency operation, the display not only reverses, but the amplitude of the laser deflection changes by approximately a factor of two. Both of these effects are easily correctable. A switch was added to the display to make it possible to reverse the deflection signals fed to the CRT, thus reversing the display, and a separate attenuator in the signal path between the horizontal generator and the main attenuator shown in figure 2 allows an amplitude correction to be made.

The attenuator shown in figure 2 serves as a display magnifier. This attenuator simply changes the amplitude of the drive signal going to the scanning mirrors, and thus causes a change in the raster size incident on the specimen without changing the raster size on the display. The display sweep signals are kept at constant amplitude. As the area on the specimen scanned by the light spot is reduced, a magnification of the area that is being scanned occurs. The attenuator controls both the vertical and the horizontal mirror excursions at the same time, and is actuated by a rotary switch arrangement with a 2-5-10 sequence.

The scan power amplifiers shown in figure 2 are commercially available units and were purchased with the scanning mirrors. These amplifiers are essentially audio amplifiers with dc coupling, and are capable of delivering 5 watts into a 5 to 10 Ω load.

4. USING THE LASER SCANNER

In this section the operation of the scanner will be described with particular emphasis on the operation of the electronics that were designed for the scanner. The mixer and pre-amplifier are described in detail, however, descriptions pertaining to the operation of purchased equipment are omitted, as these are assumed to be well known.

For many applications, the electronics of the scanner are capable of performing all of the desired measurements on a particular device or specimen. Power supplies, both negative and positive, are built into the scanner's electronics, as well as a choice of load resistors. When higher voltage or current is needed to energize a particular specimen, external power supplies can be easily interfaced with the scanner electronics.

4.1 Operation of the Electronics

As pointed out previously, the mixer is the heart of the electronic portion of the scanner. The mixer can be used with or without the pre-amplifier; it will be described as if it is to be used by itself. The front panel of the mixer is shown in figure 3. The mixer can be divided into four separate sections as shown by the dashed lines in the figure. The first section starting from the left, designated channel 1, contains the controls necessary to energize a specimen, extract the signals generated by the device when the laser spot is swept over it, and amplify these signals so that they can be displayed. This channel is for specimens that require positive voltages for excitation when the specimen is energized with the built-in supply. The supply that is built in does not have to be used and this channel can simply be used as an amplifier. The next section designated channel 2, is identical to channel 1 except that it contains a negative voltage supply for specimens that require a negative supply. Channel 3 is to the right of channel 2 and contains no power supplies. It is intended for use as just an amplifier. Signals developed by the photodiode and amplified by the reflected light amplifier are usually fed into this channel, although they could equally well go into either of the other two channels. The fourth section, which is on the right-hand side of the chassis, is the mixing section. This can be subdivided into two sections. The four controls on the top mix signals from the three channels with the vertical waveform used for deflection on the cathode ray display. The use of these controls allows the user to obtain quantitative information from the scanner, as the specimen's response can be made to appear as a vertical displacement which can be measured, whereas it is much more difficult to assign numbers to a change in spot intensity on the face of the cathode ray display. The three controls on the bottom mix the signals from the three channels so that they can be displayed in the desired proportion by intensity modulation of the beam on the cathode ray display.

It is useful to specifically identify the controls and describe their function. In figure 3, the controls are labeled for the first channel. The specimen is connected to the INPUT, usually by its lead which normally receives power when the specimen is used in a circuit in its normal function. The LOAD switch provides a choice of resistors from 330 Ω to 10 KΩ across which the specimen signals are developed by the scanning light spot incident on the specimen. A voltage, which is set by the SPECIMEN SUPPLY VOLTAGE switch is fed through the chosen load switch resistor to the specimen. This arrangement furnishes power to the specimen as well as provides for signal detection. In addition to providing load resistors, the load switch can be used to disconnect the supply from the specimen if the channel is to be used as an amplifier only. The switch is set to the OPEN position for this function. The load switch can also connect the specimen directly to the power supply. This function is useful if the specimen requires two supplies and obtains all of its power by using both channel 1 and channel 2. By using two channels on the mixer, specimen current variations caused by the light spot can be monitored on both power supply connections to the device. Under these conditions, it may be useful to connect one supply directly to the specimen while the other is monitored. The load switch position which allows this to be done is designated DIR, and in this position the mixer is capable of furnishing about 300 mA to the specimen. When the load resistors are used, experimentation is often the best course to follow in determining which resistor is the best for a particular device specimen. In general, specimens that require a greater amount of power need a smaller load resistor in order to keep the dc voltage drop across the resistor as small as possible. Unfortunately, a small resistor does not allow much signal voltage to be developed by the specimen when the light spot scans it. Specimens that have a strong photoresponse can easily produce enough signal for a good display; however, if the response is weak, a larger load resistor may be required. The specimen supply voltage switch may have to be reset to maintain the specimen at its proper operating voltage if the dc drop across the load resistor is too high. It may be useful to monitor the specimen voltage with a meter (the pre-amplifier has this provision built in). The specimen voltage switch provides a choice of five voltages from 0 to 15 volts. These voltages are approximate and should not be used to calibrate the system. The two controls in the preceding description determine in part the operation of the specimen. Neither of these controls is needed if an external power supply is used to power the specimen. If an external supply is used, an external load resistor will also be needed in most applications. It is interesting to note that the load-switch setting actually determines the input impedance to the amplifier and can be used as an attenuator, if the source impedance is not too low, when the channel is used as just an amplifier.

The remaining controls in channel 1 which are labeled in figure 3 control the operation of the amplifier portion of the channel. The OFFSET control and the OFFSET INDICATORS are used to guide the signal through the amplifier. The offset control compensates for the relatively large dc voltage that is present on the specimen so that small ac signals can be amplified. The offset indicator lamps monitor the state of the output of the amplifier and light if the amplifier is saturated by either the dc or the signal. If the amplifier is being saturated by the signal, both lamps will light, usually blinking alternately. The lighting of only one lamp indicates that the amplifier is being saturated by dc. If the dc level at the input is within 20 volts of ground, either plus or minus, the offset control can be used to compensate. Compensation of the dc level, and indication that the input signal is within acceptable limits, is shown when neither lamp is lit. The GAIN control can be used to reduce or boost the signal level, and should be set, along with the offset control, so that neither offset indicator light is lit. It is still possible to overload the input stages of the amplifier with the gain control turned all of the way down, and so an attenuator before the specimen and the amplifier may have to be used under certain conditions. The INVERT switch inverts the polarity of the signal. The output of channel 1 of the mixer is available in the rear of the equipment and is designated Z_1 out. The output of this channel is also fed to the mixing portion of the mixer for further processing. The outputs of channels 2 and 3 are also available separately as well as being fed to the mixing section.

As mentioned previously, the mixing section of the mixer has two parts. The three controls on the bottom row, labeled Z AXIS MIX-1; Z AXIS MIX-2; and Z AXIS MIX-3, provide a means by which the outputs from the various channels can be combined in any desired proportion and fed to a single output jack. This output is designated MIXED Z OUT, and is the source which modulates the intensity of the electron beam in the display. By the use of these controls it is possible to superimpose a reflected light image of the specimen on its own photoresponse. The controls for unused channels should be rotated full counter clockwise so that dc offset voltages and noise from those channels is not introduced into the display. The four controls on the top row allow the outputs from the three channels to be mixed with the vertical deflection waveform. The first three controls (from the left) are for the three channels respectively, and the fourth control adds the vertical deflection waveform which is fed to the Y FUNCTION IN jack on the rear panel. This fourth control is designated Y AXIS MIX-Y, and it can be used to adjust the raster size in the vertical direction on the display. When no signal vertical deflection is desired on the display, but intensity modulation only, the first three controls labeled Y AXIS MIX-1; Y AXIS MIX-2; and Y AXIS MIX-3, are all rotated fully counter clockwise and the fourth control is set to some level which gives a suitable vertical height to the raster on the display. This group of controls enables the user to obtain quantitative information from the scanner because the signal output from the channel or channels being used can be displayed as a vertical deflection of the horizontal scanning lines on the display, and can thus be measured. The output from this portion of the mixer is fed to the Y FUNCTION OUT jack on the rear panel, and from there it goes to the vertical input on the display. The two sections of the mixer part of the mixer chassis are independent, and one channel's signal output can be displayed using intensity modulation of the display screen, while another channel's output can be displayed using the vertical modulation technique. The identity of two separate signals from the specimen can be maintained by taking advantage of the two different display presentation techniques. The identity of three separate signals from the specimen can be maintained by connecting the individual outputs from the three channels to a color cathode ray display (see Appendix D) so that the output from each channel is presented in a different color. The pictures obtained from this tri-color display mode can be quite dramatic and revealing of specimen behavior.

Before concluding the mixer chassis description, a few other items should be discussed. The mixer incorporates the circuit for developing the blanking signal for the display. Even though the waveforms for both the vertical and the horizontal scans are symmetric, it is necessary to blank the retraces for both. A small amount of phase shift between the travel of the laser scanning mirrors and the motion of the electron beam in the display shows up as a significant error in position of the spot on display screen. If the screen is not blanked during retrace, then two images are produced, and the result is poor definition and a confusing display. For the blanking function to be performed, square-wave outputs from both the vertical and horizontal generators are fed to the HORZ IN and VERT IN jacks on the rear of the mixer. The composite blanking signal for the display is available at the BLANK OUT jack, and this is connected to the blanking input on the display screen. A couple of voltage outputs are also available on the mixer. These outputs include a 12-V output for the reflected light photo-diode and its amplifier, and plus and minus 25-V outputs for a high-impedance probe.

The pre-amplifier is really simply an extension of the mixer with a few added features to make it suitable for lower signal level extraction. The pre-amplifier's features include two channels, a high-pass filter, metered specimen supplies, continuously variable supply voltages, and a choice of FET or bipolar amplification.

The front panel of the pre-amplifier is shown in figure 4. The pre-amplifier can be divided into three sections as shown by the dashed lines. Channel 1 is used for specimen connections that use a positive power supply in much the same manner as channel 1 on the mixer can be used. Channel 2 is identical except that negative voltages are available. The pre-amplifier rather than the mixer is almost always used for specimen excitation and signal pick-up because the pre-amplifier has certain features that the mixer does not have. The mixer, however, is always used as an amplifier in the system. The outputs from the pre-amplifier channels are usually fed into the inputs on the mixer and the specimen supplies on the mixer are not used when the pre-amplifier is in the system. On the pre-amplifier, the specimen supply voltage controls are continuously variable instead of having fixed positions as they do on the mixer. The pre-amplifier is also equipped with a VOLTAGE INDICATOR METER and a METER FUNCTION SWITCH for each channel, which allow the voltage on either side of the specimen load resistor to be read with the meter. One can determine the voltage drop (the difference between the two meter readings) across the load resistor and calculate the specimen current. This can be done easily when the FILTER switch is in some position other than dc, as the amplifier input stages draw some current from the specimen supply when the switch is in the dc position. When the filter switch is in the dc position, specimen current can still be measured, but the current drawn by the input stages must be subtracted from the total current indicated by the meter when the specimen is connected. A determination of the current drawn by the input stages can be made by disconnecting the specimen and using the meter function switch and the meter to determine the IR drop across the load resistor as if a specimen current was being calculated. The LOAD, OFFSET, OFFSET INDICATORS, and GAIN controls all have the same function that they do on the mixer.

A FILTER switch is provided which affects both channels at the same time and limits the response of the pre-amplifier at low frequencies. Normally, it is desirable to have the video amplification dc-coupled since it yields a more accurate display. Furthermore, the dc coupling is a necessity when slow scanning rates are used. However, many specimens drift substantially, or produce large amounts of noise at low frequencies, and it is desirable to filter this out. Another interesting feature that the preamplifier has is an FET-BIPOLAR SELECT switch. The pre-amplifier has both an FET amplifier and a bipolar amplifier, so that the type of amplifier with the most desirable characteristics for a particular application can be used. The switch has the effect of placing the FET amplifier on channel 1 and the bipolar amplifier on channel 2 when the left-hand button is pushed, and placing the bipolar amplifier on channel 1 and the FET amplifier on channel 2 when the right-hand button is depressed. The maximum voltage gain of the FET amplifier is 400 while that of the bipolar is 100.

The FET amplifier was designed primarily as a fast recovery amplifier. It uses no negative loop feedback except when the filter is used, and then only dc feedback. This design approach allows the amplifier to be used in certain applications where it is driven into saturation by large signals which obscure more important small signals. By using the offset control it is possible to extract the desirable information by setting a window on either the most positive or most negative part of the waveform developed by the specimen. Figure 5 helps illustrate this method of signal extraction. The window, which is labeled B, is moved vertically by the offset control, and the width of the window is set by the gain control. Increasing the gain has the effect of narrowing the window. For the particular waveform illustrated, the amplifier is driven into saturation by relatively high positive voltages in the region designated A in the figure. If the waveform were to protrude into the region labeled C, the amplifier would saturate there as well. Only the portions of the waveform in the window region will be amplified. For viewing ease, the invert switch on the mixer will be set so that the portion of the waveform in region A will appear on the display screen as dark, and only areas on the specimen that cause the signal to go into the B region will be displayed. For this condition of display, one of the offset-indicator lamps will be lit or blinking on the pre-amplifier. It is important that the mixer amplifier not be driven into saturation because it is a conventional bipolar transistor design with negative feedback, and it cannot recover fast enough to preserve the accuracy of the desired portion of the signal. An output attenuator is provided on the rear panel of the pre-amplifier to make it possible to reduce the amplitude of the signal fed into the mixer. This should be used together with gain control on the mixer because as mentioned previously, the input stages on the mixer can be overloaded, even with the gain turned all of the way down.

For normal signal conditions, that is, when the pre-amplifier is not driven into saturation, the FET amplifier and the bipolar amplifier are very similar in performance. The bipolar amplifier has a slightly better signal to noise ratio, and its lower gain is often an advantage.

4.2 Specimen Connection

It is useful to look at some examples of how specimens are connected to the electronics. Figure 6 shows one way that a transistor can be connected to either the pre-amplifier or the mixer. A simplified portion of the electronics that is built into both the mixer and the pre-amplifier is shown so that it can be seen how the specimen obtains power and how the signal is picked off of the power supply line. It is usually desirable to vary the bias on the device under observation, and this may be accomplished with an external power supply. The specimen must be placed under the scanning light spot so that it is as level as possible to obtain uniform focus on the chip area. Many specimens are sensitive to room light, and the lights should be kept dim, particularly if they are of the fluorescent type, as the line frequency modulation of the room light is readily transformed into a modulation of the specimen signal by the specimen. Figure 7 shows a typical connection when it is desirable to power the device under observation entirely with external supplies. For this application the load switch should be set to the highest load position or to the "open" position on the mixer. If the external supply used is a high-voltage unit, the specimen signal voltage entering the mixer or pre-amplifier should be blocked with a capacitor or divided with a resistive network to keep high voltages out of the pre-amplifier or mixer. Alternatively, for the example shown in figure 7, the specimen signal can be picked off across the emitter resistor. Figure 8 shows a typical scheme for energizing and scanning an integrated circuit. The power supply lead for the device is connected to the pre-amplifier and powered by it. The inputs and outputs on the integrated circuit are connected as necessary to make the circuit function in its normal manner. A typical specimen connection for a device requiring dual power supplies is shown in figure 9. It is often desirable to terminate the inputs to a high-gain linear device with low resistances, otherwise a very large signal is obtained from the input transistors.

4.3 Magnification and Achievement of Optimum Definition

The optimum definition, that is, the maximum number of distinct objects that can be seen on the display, is obtained by setting the attenuator that controls the scanning mirror excursion so that the mirrors have the largest excursion without the light raster being vignetted by the microscope optics. These conditions are best satisfied by setting the attenuator on 1000 μm regardless of which microscope objective is used. This 1000 μm position is calibrated so that the raster size on the specimen will be 1000 μm x 1000 μm when the 8X objective is used in the microscope. By switching the attenuator to the 500 μm position, the magnification is doubled. The picture definition is degraded however because of the non-zero spot size. The preferred method for changing the magnification is to change microscope objectives. It is important to remember that the markings on the attenuator are referenced to the 8X objective, and if a 16X objective is substituted for the 8X objective, and the attenuator is set on the 1000 μm position, then the raster size on the specimen will be 500 μm x 500 μm. The attenuator is of course very useful for electronically magnifying a portion of the specimen and measuring particular portions. An additional item that must be noted is that the markings on the attenuator are valid for the normal, 1.2 kHz horizontal and 3 to 4 Hz vertical scanning rates because, as previously described, the horizontal scanning mirror is operated slightly beyond resonance so that decreasing the scanning rate changes the amplitude of the excursion of that mirror.

4.4 Optimizing Scanning Rates

In general it may be best to use the fastest scanning rates that the scanning mirrors will allow because it is important that a picture of the specimen is produced in the shortest possible time. This reduces the effects of drift in the specimen or electronics and is particularly appropriate when the display is being photographed. The fast scanning rates also make it easier to view the display in real time, especially the color display because fast-decay phosphors are used.

Many specimens have carrier storage effects which make it necessary to use slower scanning rates to maintain resolution. Situations where these storage problems occur are usually made apparent by blurring of vertical lines in the image. Solar cells are particularly susceptible to these storage problems. On certain specimens there is a strong dependence on the storage time and bias. Increases in reverse bias voltage on the specimen usually shorten this storage time. As mentioned in the section of this report dealing with the principle of operation of the scanner, the horizontal scanning mirror normally is operated beyond resonance at 1.2 kHz. It was also stated that reducing the horizontal scanning rates not only changes the magnification in the horizontal direction, but also reverses the picture in such a way that the left-hand side of the picture becomes the right-hand side and vice versa. It must also be remembered that the 1.2 kHz is the frequency where picture linearity is obtained by virtue of 180 deg. out of phase operation between the mirror movement and the electron beam movement in the display. When the scanning rates are changed to slower ones, usually only the frequency multiplier knob on the horizontal generator is disturbed because of the rather fine tuning required to find the 180 deg. phase shift needed for picture linearity. Thus sweep rates of 1.2

kHz, 120 Hz, or 12 Hz are usually used. The vertical generator for the frame rate can be set to any frequency.

4.5 Getting the Picture - A Quick Guide

Presented below is a list of the steps that can be taken to obtain a monocromatic picture of a particular specimen as quickly as possible.

1. Energize scanner with main power switch.
2. Set knobs on the MIXER, from the left-hand side of the unit, as follows:
   a. Channel 1 OFFSET - any position
   b. INVERT switch - either up or down
   c. GAIN - 9 o'clock
   d. VOLTAGE switch - GND
   e. LOAD - 10k
   f. Channel 2 controls - same as channel 1 controls
   g. Channel 3 (reflected light) GAIN - 3 o'clock
   h. INVERT - up
   i. OFFSET - so that both offset indicator lights are extinguished
   j. Y-AXIS MIX 1, 2, and 3 - full counter-clockwise
   k. Y-AXIS MIX-Y - 2 o'clock
   l. Z-AXIS MIX 1,2, and 3 - full counter-clockwise
3. Set knobs on the PRE-AMPLIFIER, from the left-hand side of the unit, as follows:
   a. METER - SUP
   b. OFFSET - any position
   c. +SUPPLY - full counter-clockwise
   d. LOAD - 3.3k
   e. GAIN - 9 o'clock
   f. CUT OFF - 10 Hz
   g. FET - BIPOLAR select switch - either position
   h. Channel 2 controls - same as channel 1 controls
   i. Attenuator controls on rear of unit - 12 o'clock
4. Set brightness on display so that a dim raster can be seen.
5. Set Magnifier/Attenuator on 1000 μm
6. Install 8X objective in microscope.
7. Place specimen on microscope stage.
8. Use figures 6 through 9 in this report as a guide and connect the specimen to the input of the pre-amplifier - use channel 1 for those devices that require a positive supply, and channel 2 for those devices that require a negative supply.
9. Connect the output of channel 1 of the pre-amplifier to the input of channel 1 on the mixer. Do the same for channel 2 of both units.
10. Set the movable slide in the microscope so that the laser is blocked and the eyepiece is activated, energize the lamp in the vertical illuminator, and focus the microscope onto the specimen.
11. Reset the prism slide so that it allows the laser to impinge on the specimen, and turn off the illuminator.
12. See that the scanner is working by using the reflected light signal. Rotate the Z AXIS MIX-3 control clockwise to obtain a reflected light image of the specimen. Adjust the offset control to extinguish the offset indicators to compensate for drift if necessary.

13. Set the SUPPLY voltage control on the channel being used to the desired operating voltage for the specimen.
14. The METER switch can be set on SAM so that the actual voltage on the specimen is monitored. If the specimen is a transistor, changing the bias (figure 6) will cause this voltage to change. If the specimen is an integrated circuit, it may be desirable to change the load switch to select a smaller resistor so that there is less voltage drop across the load. It may also be desirable to increase the voltage to compensate for the drop.
15. Adjust the OFFSET control on the pre-amplifier of the channel being used so that both offset lamps are extinguished. If both lamps cannot be extinguished, reduce the gain so that both lamps can be extinguished with the offset control.
16. Adjust the OFFSET control on the mixer for the channel being used. Follow the same procedure as above. It may be necessary to reduce the gain on the pre-amplifier further to avoid overloading the input stages of the mixer.
17. Rotate the Z-AXIS MIX 1(or 2 if channel 2 is used) clockwise to obtain a display of the photo response of the specimen. It may be necessary to increase the gain on one or both of the units. Remember that there are also attenuators on the rear of the pre-amplifier.
18. The photo-response image can be superimposed on the reflected light picture by using the Z-AXIS MIX knobs as desired. The Y-AXIS MIX controls can be used to obtain the vertical deflection type display.

If the color display is to be used, the OFFSET on each of the three channels controls the level of the three primary colors, red, blue, and green. The Z-AXIS MIX and the Y-AXIS MIX controls are not used.

5. OPTICAL ALINEMENT

Optical alinement should be performed to some extent when the scanner is moved, when a laser is changed, or when the scanner is subjected to excessive vibration. The following is a complete listing of the steps for alinement of a new instrument; many of these steps can be omitted for realinement purposes.

*CAUTION: Care must be exercised to avoid having either the infrared laser radiation or the visible laser light reflected into the eye.

1. All power to the scanner should be off. Set the mirrors, both the stationary ones and the scanning mirrors, to their approximate positions needed to cause the laser radiation from the infrared laser to be deflected down the camera tube of the microscope. Use figure 1 as a guide to the deflection sequence.
2. Energize only the vertical illuminator lamp in the microscope. Adjust the four screws at the base of the scanner which set the height of the scanner mainframe relative to the microscope and microscope stand. The screws should be adjusted so that the camera tube passes through the center of the hole in the top of the scanner frame. The screws must also be adjusted so that the light from

the vertical illuminator comes to a point on the scanning mirror directly above the camera tube. The prism in the microscope must be set so that the light passes through the camera tube and not to the eyepieces.

3. Turn off the vertical illuminator lamp and energize the infrared laser. Using an IR phosphor card, guide the infrared laser radiation through the optical system and through the microscope by adjustment of the mirrors. Aim the radiation down the center of the camera tube. Slightly adjust the screws at the base of the scanner so that the radiation passes through the center of the microscope optics onto the stage.
4. Activate the visible laser and move the slide which changes the laser sources to the position that blocks the infrared laser. Adjust the position of the two mirrors on this slide so that the visible light beam follows the same path as the infrared light beam from the scanning mirrors and through the microscope. Do not disturb any other adjustments. By switching back and forth between the two lasers, make the spot from the two lasers hit the microscope stage at the same point.
5. Turn on the generators and the scanning mirror drivers. Set the magnifier so that the scanning mirrors have large enough excursions so that the raster formed on the microscope stage by either laser has some of its corners cut off. Adjust the screws at the base of the scanner so that all four corners of the raster are equally cut off - that is, center the raster. Lock the adjustment screws at the base of the scanner.
6. Adjust the half-silvered mirror and lens in the reflected-light circuit so that the raster degenerates to a point on the active area of the photo diode.
7. Energize the remainder of the electronics and adjust the $\lambda/2$ plate to maximize the output from the reflected light circuit when the infrared laser is used.

6. ACCESSORIES

6.1 Radio Receiver

A specimen's response to VHF and UHF frequencies can be conveniently studied with the use of a radio receiver in place of one preamplifier channel in the scanning system [6][9]. The lasers are self modulated due to their basic principles of operation, and the visible laser used in the NBS system has useful modulation components at 0.5 GHz and 1.0 GHz, while the near infrared laser has useful components at 385 MHz and 770 MHz. The laser spot effectively embeds a signal generator in the specimen which has both a dc component and a high-frequency component. The dc component gives the conventional display results; however, when a radio receiver is connected to the specimen, a map of the response of the device at the laser modulation frequency may be obtained. The radio receiver is tuned to either of the two useful modulation frequencies for the laser being used. Figure 10 shows a typical hook up for a specimen so that both the video information and the high frequency information can be contracted at the same time. The output from the radio receiver is fed into an unused channel in the mixer for display.

6.2 Laser Modulator

As an extension to the radio receiver concept, a dc to 100 kHz laser modulator was added to the system. The modulator is capable of at least a 10% depth of modulation. The modulator permits the response of the specimen to be studied at frequencies up to 100 kHz; however, much longer scanning times must be used as the signal bandwidth is limited. A lock-in amplifier can be substituted for the radio receiver to detect the desired signal[10]. The circuit for the modulator is given in Appendix E.

6.3 High Impedance Probe

Certain applications in optical scanning require the use of a high-impedance probe to minimize disturbance of the scanned specimen. Such a probe is shown schematically in Appendix E. The probe features dc coupling and can pass signals riding on dc voltages when these dc voltages are as high as 20 V and as low as -20 V. The probe loads the circuit being measured with 3.1 pF at 1 MHz and 22 MΩ at dc. The probe obtains its operating power from the mixer.

7. SPECIFICATIONS

1. Optical radiation sources
   a. 0.6328 μm He-Ne laser
      3 mW power output at 0.6328 μm, polarized
      Lowest axial mode modulation frequency: 500 MHz
      External modulator: dc to 100 kHz at 10% depth of modulation
   b. 1.15 μm He-Ne laser:
      2 mW power output at 1.15 μm, polarized
      Lowest axial mode modulation frequency: 385 MHz
2. Optical power at the specimen (approximate)
   a. 0.6328 μm laser, referenced to 3 mW
      with 4x objective, 0.3 mW; NA = 0.1
      with 8x objective, 0.36 mW; NA = 0.2
      with 16x objective, 0.16 mW; NA = 0.35
      with 40x objective, 0.15 mW; NA = 0.6
   b. 1.15 μm laser, referenced to 2 mW
      with 4x objective, 0.12 mW
      with 8x objective, 0.15 mW
      with 16x objective, 0.15 mW
      with 40x objective, 0.10 mW
3. Resolution (This is a measure of the system's ability to separate closely-spaced features and it varies both with the laser wavelength and microscope objective chosen. Appendix F describes in detail how the following resolution values were obtained and defined).
      λ = 0.6328 μm; 40 x objective;
         2 μm spaced lines yield 30% resolution.

λ = 1.15 μm; 40 x objective;
2 μm spaced lines yield 18% resolution.
λ = 0.6328 μm; 16 x objective;
3.12 μm spaced lines yield 30% resolution.
λ = 1.15 μm; 16 x objective;
4 μm spaced lines yield 13% resolution.
λ = 0.6328 μm; 8 x objective;
4 μm spaced lines yield 13% resolution.
λ = 1.15 μm; 8 x objective;
8 μm spaced lines yield 10% resolution.
λ = 0.6328 μm; 4 x objective;
16 μm spaced lines yield 50% resolution.
λ = 1.15 μm; 4 x objective;
16 μm spaced lines yield 13% resolution.

4. Scanning rates
   a. horizontal
      3 mHz to 100 Hz without incurring significant distortion, and 1.2 kHz
   b. vertical
      3 mHz to 100 Hz
5. Mixer specifications
   dc to 2 MHz frequency response
   up to 34 dB gain on each channel
   0, 3, 5, 12, 15 V specimen bias
   0, -3, -5, -12, -15 V specimen bias
   0 Ω, 330 Ω, 1 kΩ, 3.3 kΩ, 10 kΩ specimen loads
   ± 20 V offset compensation
   input impedance 100 kΩ maximum
   output impedance <250 Ω on all signal outputs
6. Pre-amplifier specifications
   dc to 2 MHz frequency response
   up to 52 dB gain FET fast recovery channel
   up to 40 dB gain channel
   0 to 20 V specimen bias
   0 to -20 V specimen bias
   0 Ω, 330 Ω, 1 kΩ, 3.3 kΩ loads for specimen
   ± 12 V offset compensation at full gain setting (compensation range increases from this as gain is reduced)
   input impedance 3.3 kΩ maximum
   output impedance 3.5 kΩ maximum

8. REFERENCES

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APPENDIX A

Commercial Equipment Used

This section contains a list of the commercial equipment that was used to build the scanner. The equipment was selected with the aim that the scanner should be extremely versatile.

1. Microscope Equipment
   a. Binocular microscope suitable for use with polarized light; including camera tube, vertical illuminator port, and prism slide to change optical paths between specimen and camera tube. The microscope has a large stage travel and a large working distance.
   b. 12.5X eyepiece oculars.
   c. 4X(NA=0.1), 8X(NA=0.2), 16X(NA=0.35), and 40X(NA=0.6) objectives.
   d. 10X camera tube ocular.
2. Signal Generators
   a. Waveforms: Sine, square, and triangle, ramp, and sync pulse, available simultaneously.
   b. Frequency: 0.005 Hz to 1 MHz.
   c. Output impedance: 600 Ω or lower.
3. Lasers
   a. 0.633 μm, 3 mW cw HeNe, noise less than 2%.
   b. 0.633 μm, 5 mW cw HeNe, noise less than 2%, mirrors changed to cause it to operate at 1.15 μm.
4. Analyzer
   Rotatable polarizing optical component.
5. Half-Wave Plate
   Mica-between-glass type for 1.15 μm radiation.
6. Monochromatic Display
   a. Bandwidth: dc to 20 MHz on X, Y, and Z inputs.
   b. Digital dc blanking, blanked +5 V, unblanked -5 V.
7. Scanning Mirrors and Amplifier Systems
   a. Galvanometric type nodding mirrors.
   b. Frequency response dc to 1 kHz.

APPENDIX B

Reimaging Lens System

The reimaging lens system which is placed between the vertical and horizontal scanning mirrors must refocus the laser beam deflection from the vertical scanning mirror to a point on the horizontal scanning mirror. This is done so that this mirror can be made small for relatively fast scanning rates. As the laser radiation leaves the horizontal scanning mirror, it emerges as a beam deflected in both the vertical and horizontal directions. An additional requirement of the lens system is that the laser radiation impinging on the second scanning mirror must consist of parallel light rays. To satisfy these requirements two lenses back-to-back are used between the vertical and horizontal deflection mirrors[7,8] to form the composite lens system L1. The distance between the vertical deflection mirror and the first principal plane of the first lens is made equal to the focal length f_1, and the distance between the first principal plane of the second lens and the horizontal deflection mirror is made equal to f_2, the focal length of the second lens. The separation between the second principal planes of the two lenses is set equal to $f_1 + f_2$. The characteristics of the lenses used were:

$$f_1 = 50 \text{ mm}$$
$$f \text{ number} = 2$$

and

$$f_2 = 25 \text{ mm}$$
$$f \text{ number} = 1.4$$

Both are TV camera lenses. Figure B1 shows the two lenses and the scanning mirrors. The vertical scanning mirror is on the left.

APPENDIX C

Mechanical Construction

The scanner is designed to be compact, rugged and portable. All equipment required to operate the scanner in any of its services is easily contained on a 2 by 1 meter work bench. It was not found necessary to shock-mount the scanner, or choose a special location to ensure freedom from perturbing influences such as building vibration. The purpose of this appendix is to present enough information on the mechanical design and construction of the scanner so that others may also build scanners with these desirable attributes.

A heavy-duty microscope stand serves as the mounting support for all the mechanical items. Most of the scanner components are attached to a rigid, reinforced frame bolted to the stand. With this construction, the entire apparatus tends to move in unison in response to outside mechanical influences, and this minimizes blurring of the scanner images by unwanted deflection of the laser spot on the scanned specimen.

In the figures which follow, all dimensions are in millimeters and, unless noted otherwise, the construction material is aluminum. Figures C1 - C8 are mechanical drawings of the scanner and the location of the items to be described subsequently can be inferred from the photos in figures C9 - C17.

Figure C1 shows the support frame. The vertical dimension indicated as 435 mm is tailored to the particular microscope used so that the axis of the horizontal scanning mirror is at the exit pupil point of the microscope camera tube. In general, the mounting holes will vary with the particular choice of the vendor selected to provide items such as lenses and galvanometer deflectors. These choices will also influence the dimensions shown for the mounting hardware in the following figures.

Figure C2 shows the holder for the horizontal scanning galvanometer mirror. It is designed to allow rotation of the galvanometer around the axis of its mirror during alinement of the system.

Figure C3 shows the holder for the two lenses making up the system described in the main text and in Appendix B. The clamps allow the center-to-center spacing of the lenses to be varied, and the oval holes allow the assembly to be moved for system alignment.

Figure C4 shows the holder for the vertical scanning galvanometer mirror.

Figure C5 shows the bracket in which is mounted the holder for mirror M1.

Figure C6 is an assembly view of the moveable slide which changes the scanning service from one laser to the other. Two small, rectangular mirrors are alined within the assembly. The small item in the upper left is one of the two identical mirror mounts. Each is glued to an edge of its associated mirror, and the mirrors are locked in position with thumbscrews.

Figure C7 shows the holder for the 1.15 μm half-wave plate. The plate is first mounted in a metal ring which may then be rotated within the cut-out portion of the holder during system alinement and then locked with a thumbscrew.

Figure C8 is an assembly view of the clear plastic cover. The projections on the bottom fit the support frame top surface. The cover protects the alinement adjustments and it also prevents dust from settling on the optical surfaces thus relaxing the cleanliness requirements on the room in which the scanner is located.

Figure C9 is an overall view of the apparatus showing the proportions and the spatial relations of the various items comprising the scanner.

Figure C10 is a top view which includes all the items used to deflect the laser beams in the raster patterns. Also shown are the locations of the assemblies which are drawn in figures C-2 through C-7. The terminal strip in the upper left is used to anchor the electrical loads to the galvanometer.

Figure C11 is a closeup of the deflection system between the vertical deflection scanning mirror and the microscope camera tube. The latter extends through a hole in the support frame.

Figure C12 is a rear view of the support frame top. The half-wave plate is in the foreground, and mirror M2 is on its right.

Figure C13 is an end view from the left of the support frame top. The slide assembly is in the center, and the vertical mirror galvanometer and lens assembly L1 are in-line on the right. The circular item below the slide assembly is the holder for the rotatable analyzer used to adjust the intensity of the 0.6328 μm scan.

Figure C14 shows the clamps locking the microscope to the base plate, and the base itself (both supplied by the microscope manufacturer). Also shown is the screw arrangement used at all four corners of the support frame which allows precise alinement to be made of the scanning system as described in the main text.

Figure C15 is a rear view of the scanner apparatus. It shows most clearly the position of mirror M1. The reflected light circuit lens L_2 and photodetector amplifier can be seen attached to the support frame to the right of the microscope.

Figure C16 is a closeup of the items used for the reflected light circuit. The 5 cm focal length lens L_2 focuses the reflected light to a pinpoint on the germanium photodiode mounted in the center of the 5 by 9 centimeter box which contains an amplifier for the photodiode. The BNC signal output cable was disconnected for photographic clarity.

Figure C17 is a view into the vertical illuminator port with the illuminator removed. A half-silvered mirror was mounted in a metal frame which fits snugly in a slot intended for an optical filter in the illuminator port. The mirror can be adjusted and locked into position with a thumbscrew. The frame on which the half-silvered mirror is mounted can also be rotated. The mirror is adjusted so that light reflected from the specimen during scanning is directed to a germanium photodiode where it is focused to a point. With proper adjustment of the 5 cm lens in this light path, the point is stationary on the photodiode during scanning of the specimen.

APPENDIX D

Color Monitor

The color monitor was made by rebuilding an inexpensive color TV set. The TV set served as a convenient source of parts rather than serving as equipment to be modified. None of the original circuits in the TV were used, however, in starting with a TV, the advantage of having a color CRT mounted in a cabinet complete with degaussing coil, purity yoke, deflection yoke, convergence yoke, and radiation shielding is realized. The TV used for the project was a small-screen tube-type set with in-line guns in the picture tube. The in-line guns simplify color convergence. Three basic circuits are needed to make the color monitor. These include the deflection amplifiers, the video amplifiers, and the high voltage power supply for the anode of the CRT.

The deflection amplifiers were built on a separate chassis, and the remainder of the circuits were built in the cabinet that contains the CRT. The identical vertical and horizontal deflection amplifiers are essentially class B audio power amplifiers with current sensing rather than the usual voltage sensing for feedback control. Figure D1 is the schematic for a deflection amplifier and its associated power supply.

The deflection yoke is almost totally an inductive load so some special considerations had to be taken into account when designing these amplifiers. The most important consideration is that the beam deflection be proportional to the current passing through the yoke and not the voltage across it. Therefore, the amplifier should be a voltage to current converter. A low value resistor in series with the yoke provides a negative feedback signal that causes the high gain amplifier to perform the conversion. Since the yokes made for the various makes and models of TV sets are all different in terms of dc resistance, number of turns, and voltage required to achieve a given beam deflection, certain parameters of the amplifier given in figure D1 may need to be adjusted to match it to a particular yoke. It was experimentally determined what current was needed to provide about a 50% overscan at dc or low frequencies, and what voltage was needed to provide a similar overscan at the highest scanning frequency that would be used. When the yoke was connected to a dc power supply, a 2 A current was needed to deflect the spot on the CRT from the center to the edge of the screen. It was concluded that the amplifier should therefore have current limiting at plus or minus 3 A.

An audio power amplifier was used to determine the ac requirements of the yoke at 1.2 kHz which is the highest operating frequencies of the scanning mirrors. It was found that with a 1.2 kHz sine wave about 14 V peak-to-peak was needed to give a full screen deflection. It was concluded that 21 V peak-to-peak would provide enough overscan. An overall supply voltage of about 24 V should allow for circuit losses, so that plus and minus 12 V supplies were made to operate the amplifiers. The dc resistance of the horizontal winding of the particular yoke used was 1.6 Ω, and the resistance of the vertical winding was 2 Ω. The lower frequency frame rate is used on the vertical winding, so that the current-deflection measurement should be done using this winding. Similarly, the higher frequency measurement should be performed on the horizontal winding. The 0.2 Ω emitter resistors for the output transistors set the current limiting point. If these are increased in value, the amplifier will current limit at lower current values. The maximum voltage that can be delivered across the yoke is limited by the power supply. The circuit should work equally well with higher supply voltages. However, all resistors except those to the left of the diode bias string in figure D1 should be increased in value as the supply voltage is increased. For the particular set that was rebuilt to make the monitor, the horizontal deflection winding and a winding on the color convergence yoke were connected in series. This connection was not disturbed, and the deflection amplifier output goes through both yokes.

The high-voltage supply for the CRT used has to supply approximately 18 kV for the anode and 680 V for the focus element. The horizontal output stage for most black and white large screen TV sets made during the last fifteen years generates these voltages. An easy approach to obtaining such a supply is to use the parts from such a TV, since such a supply uses many special inductors and high voltage parts. Figure D2 shows a simplified schematic of such a circuit. Also shown in the figure is the power supply for the high-voltage circuit and the other circuits in the monitor. An inductor must be connected to the high-voltage transformer in the place where the deflection yoke is normally connected, as this is a tuned circuit. Due to the high voltage and current demands on the inductor, the deflection yoke from the black and white TV was actually used. The part was mounted as far away as possible from the CRT so that it would not deflect the electron beam in the CRT. The yoke must be mounted in such a manner that there are no conducting materials in the hole where the CRT normally goes. The power transformer also generates fields that can deflect the electron beam or cause color purity problems, so this part should also be mounted as far away as possible from the CRT.

The schematic for the video amplifiers and blanking circuit is given in figure D3. The dual-gate MOS transistors are depletion devices and are of the type that have integral protection diodes. A negative voltage bias is required for the input gate of the blanking circuit. The grid of the horizontal output tube conveniently provides a source for this bias. The 12 Vac required for the CRT heater must be provided from a separate winding on the power transformer (or a separate transformer) because the heater should be at a dc potential close to that of the cathode.

APPENDIX E

Circuit Schematics

The electronic circuits for the scanner were designed to handle a wide variety of specimen-measurement situations. All of the circuits feature dc coupling with temperature-drift compensation with the exception of the single-stage photodiode amplifier which does not have drift compensation. All of the circuits utilize regulated power supplies. These features make it possible to achieve a high degree of display accuracy even when slow scanning rates are used. Both the mixer and the preamplifier feature a wide dc offset nulling capability with indicator lamps to enable fast and accurate compensation for the dc voltages present on the specimen. The wide offset range and indicator lamps have been found to be indispensable.

Figure E1 is the block diagram and figure E2 is the schematic diagram of the mixer. High-voltage video-amplifier transistors are used extensively throughout the mixer. One reason for using such transistors is that the immunity to high-voltage transients accidentally applied to the input is improved. The particular transistors used are fast enough so that the amplifier has a flat response to about 2 MHz, but slow enough so that high frequency instabilities do not occur.

Figure E3 is the block diagram and figure E4 is the schematic diagram of the preamplifier. The preamplifier uses a tightly-regulated power supply for improved performance at low signal voltage levels. Actually, three voltage regulators are used for each voltage polarity. The first regulator for each voltage polarity is a pre-regulator which provides the other two regulators with a relatively clean, constant voltage. The second regulator provides a very clean voltage to operate the amplifier circuits and also provides a voltage reference for the third regulator. The third regulator supplies the specimen with the required operating power and can be adjusted anywhere between 0 and 20 V for the positive-polarity regulator, and 0 and -20 V for the negative-polarity regulator. A high-pass filter is included in the preamplifier. This filter is a double-pole type which inserts a coupling capacitor in the input circuit as well as inserts a capacitor in the feedback loop. A switch is also included in the preamplifier which allows the type of amplifier to be changed without disconnecting the specimen or disturbing the specimen voltage settings. Either a conventional bipolar transistor amplifier or a fast recovery FET amplifier with no loop ac feedback can be used. There are two sections on this switch and the section which switches the input signal is located physically toward the front of the chassis and the section which switches the output is located toward the rear of the chassis. A long connecting rod operates the two sections in unison. The physical separation ensures freedom from oscillation. Output attenuators are located on the rear of the preamplifier chassis. The gain-bandwidth product of the circuits in both the preamplifier and the mixer is quite large, and construction should be attempted only by persons familiar with such circuits.

The attenuator-magnifier schematic for the electronic magnification of the specimen is shown in figure E5.

Figure E6 is the schematic for the reflected-light amplifier with the germanium photodetector. This circuit obtains its operating power from the mixer.

The schematic for the dc to 100 kHz laser modulator is shown in figure E7. A novel approach to high voltage control is used in the modulator. The screen of a tube designed for horizontal output service in television sets is driven with direct-coupled circuitry to yield a reliable high voltage switch. The grid and cathode are connected together in this scheme. As a result, the common failure mode of grid to cathode short, which is the real voltage limiting factor in such devices, is eliminated, and the voltages commonly used in gas lasers can easily be switched.

Figure E8 is the schematic for the high impedance probe which can be used in applications where device loading is important. The probe obtains its operating power from the mixer.

APPENDIX F

Resolution - How It Is Defined

In the specifications section of this report the resolution figures are specified as percentages. Figure F1 helps explain the meaning of these numbers in terms of measurable quantities. Figure F1a shows the detector output as a function of laser spot position on a resolution test target if the resolution were perfect. The test target contains both widely spaced bars which serve as a reference, and closely spaced bars with a separation d. The distance d is the test pattern line spacing to which the resolution is referenced in the specifications. Figure F1b shows a typical output which is obtained from the detector due to the finite resolution of the system. The resolution given in the specifications is defined as

$$R \equiv \frac{100\ Y}{X}\ \%.$$

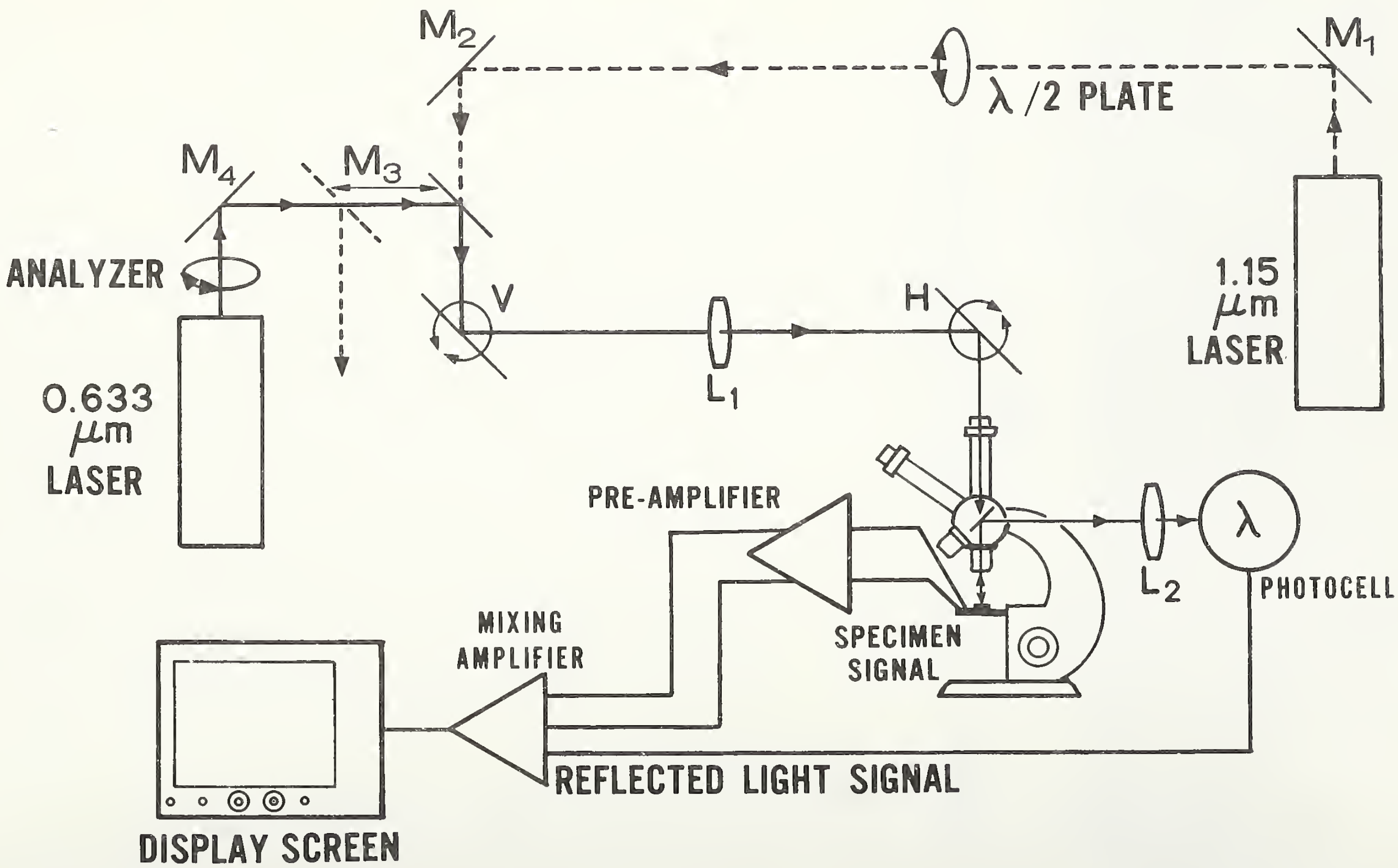


Figure 1. The light and signal paths of the dual-laser scanner.

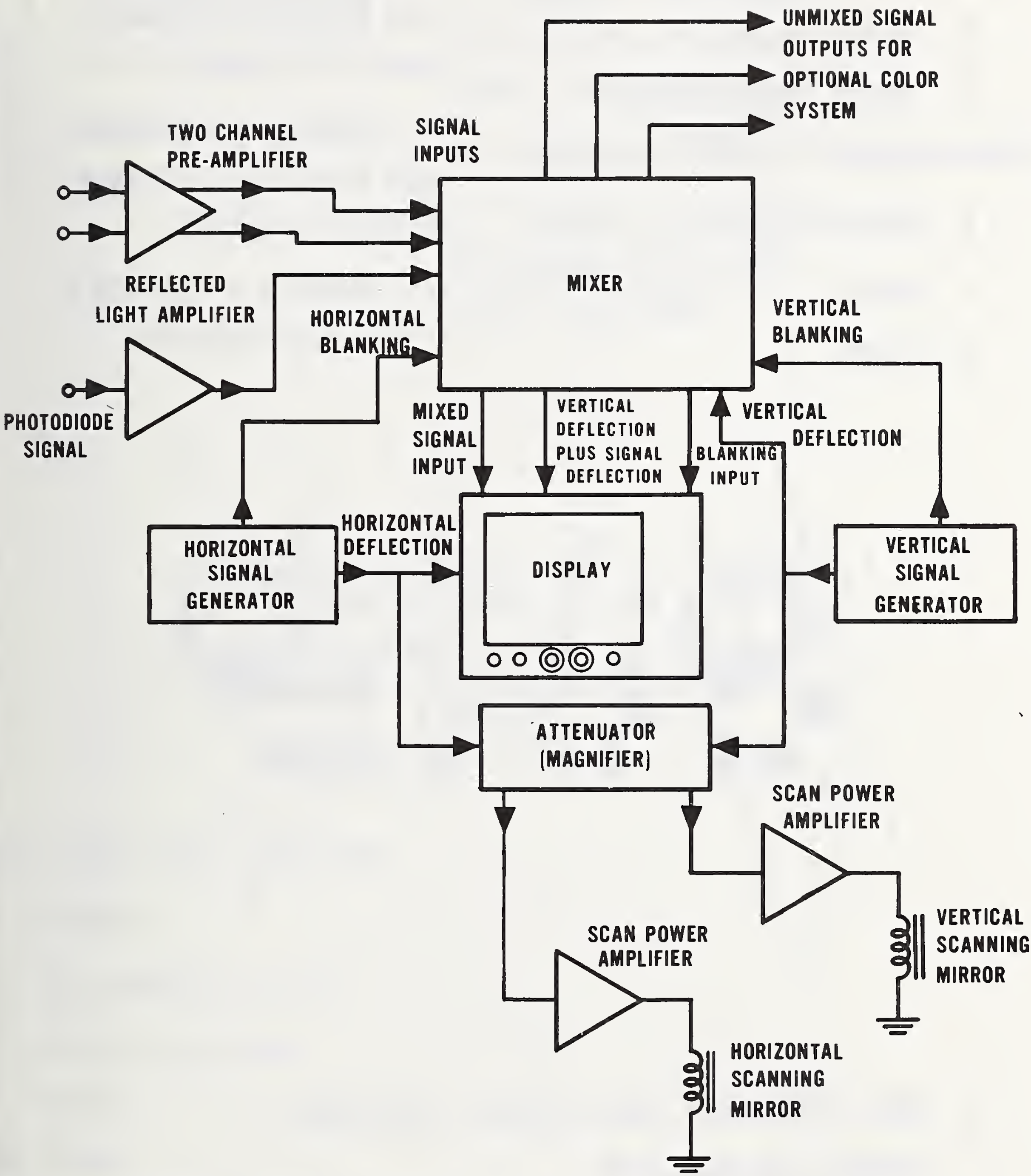


Figure 2. A block diagram of the electrical interconnections for the scanner.

A - SPECIMEN SUPPLY VOLTAGE

B - OFFSET

C - OFFSET INDICATORS

D - INPUT

E - INVERT

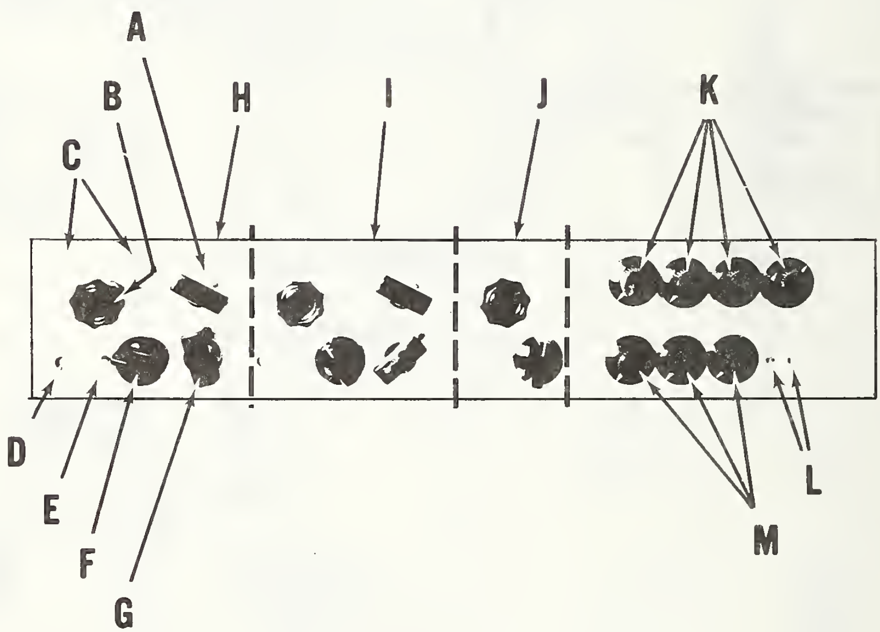
F - GAIN

G - LOAD

H - CHANNEL 1 CONTROLS FOR POSITIVE SPECIMEN SUPPLY VOLTAGES

I - CHANNEL 2 CONTROLS FOR NEGATIVE SPECIMEN SUPPLY VOLTAGES

J - CHANNEL 3 CONTROLS FOR REFLECTED LIGHT



K - MIX 3 CHANNELS AND VERTICAL WAVEFORM

L - POWER AND INDICATOR

M - MIX 3 CHANNELS INTO COMPOSITE Z OUT

Figure 3. Mixer controls.

A - VOLTAGE INDICATORS

B - OFFSET INDICATORS

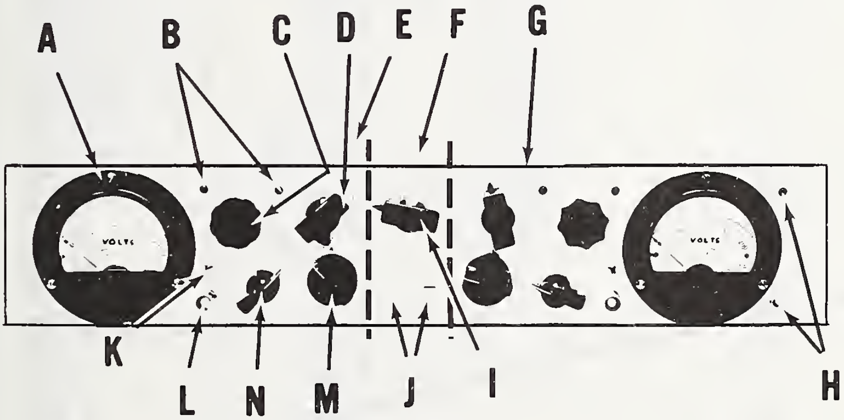
C - OFFSET

D - LOAD

E - CHANNEL 1 CONTROLS FOR POSITIVE SPECIMEN SUPPLY VOLTAGES

F - CONTROLS COMMON TO BOTH CHANNELS

G - CHANNEL 2 CONTROLS FOR NEGATIVE SPECIMEN SUPPLY VOLTAGES



H - POWER AND INDICATOR

I - FILTER

J - FET-BIPOLAR SELECT

K - METER FUNCTION

L - INPUT

M - GAIN

N - SPECIMEN SUPPLY VOLTAGE

Figure 4. Pre-amplifier controls.

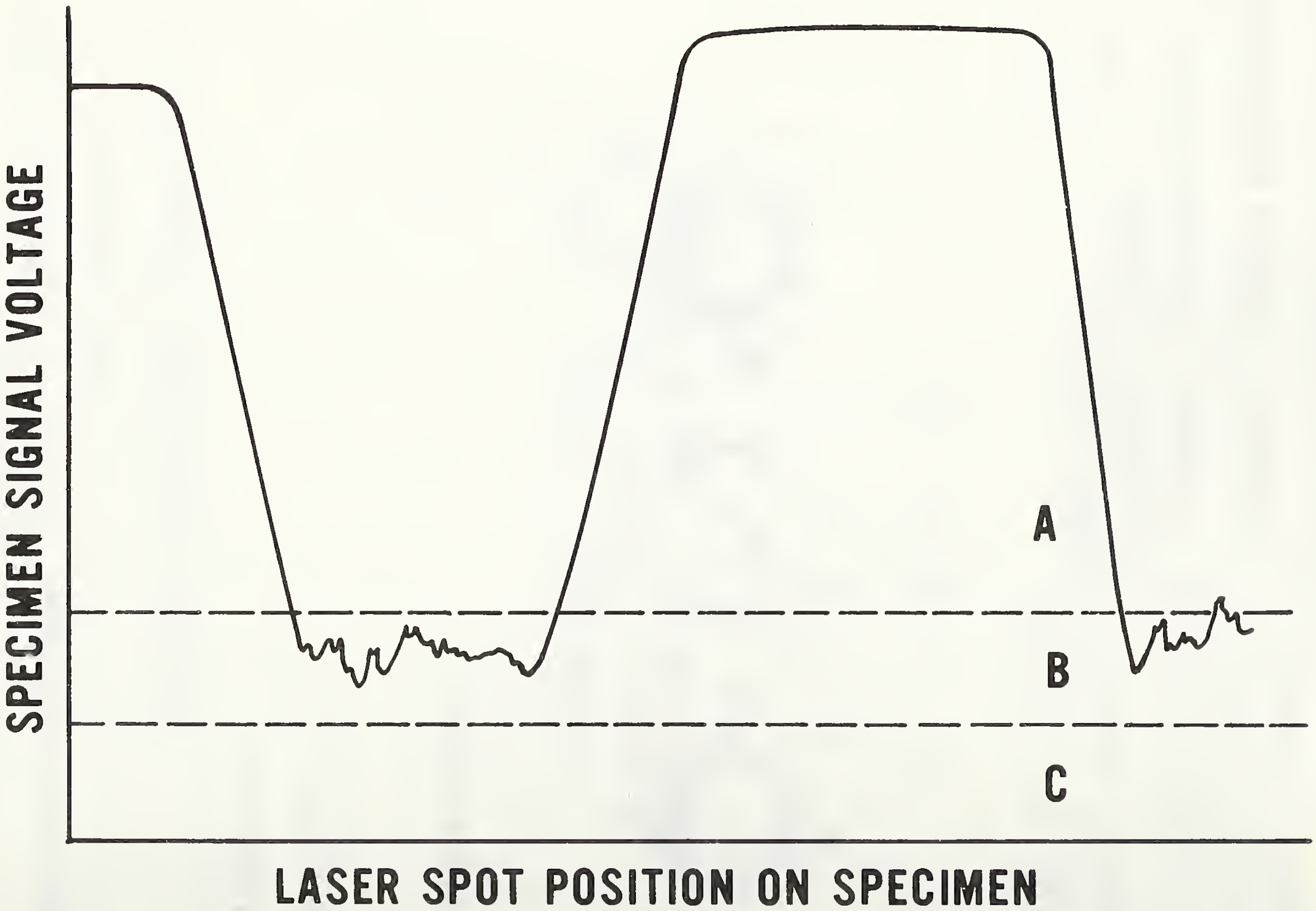


Figure 5. Using the electronics to extract a small signal from a large one. The offset control on the pre-amplifier is set so that only specimen signal voltages that fall in the B region are amplified.

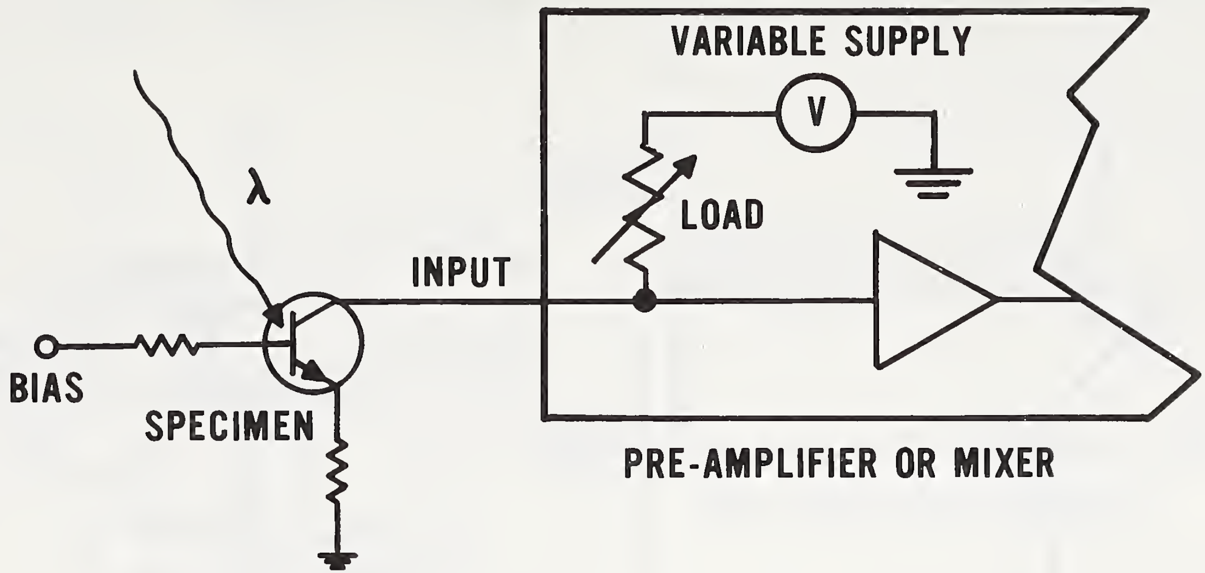


Figure 6. Typical hookup of specimen to electronics.

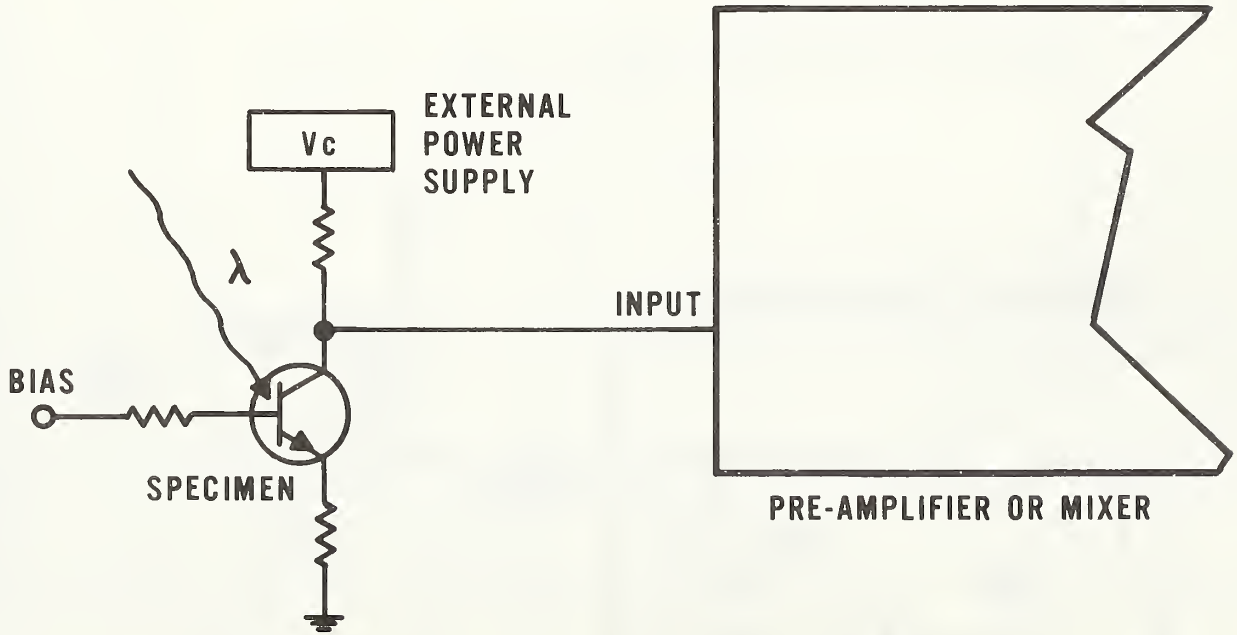


Figure 7. Hookup of specimen to electronics when an external power supply is used.

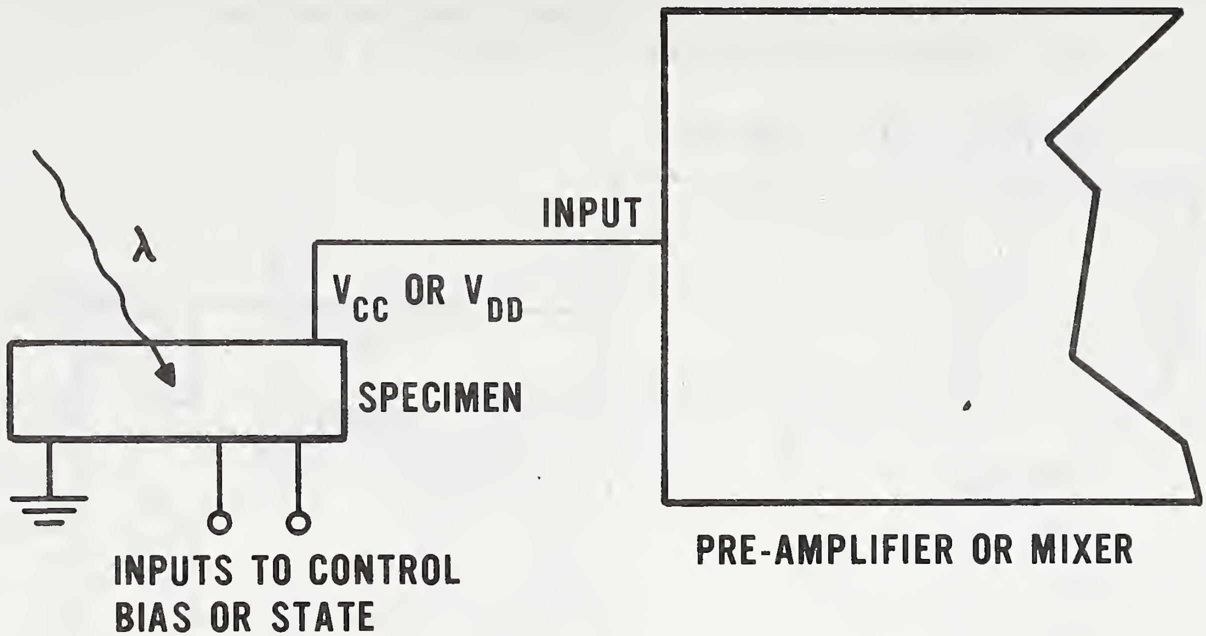


Figure 8. Connection of a typical integrated circuit specimen to the scanner's electronics.

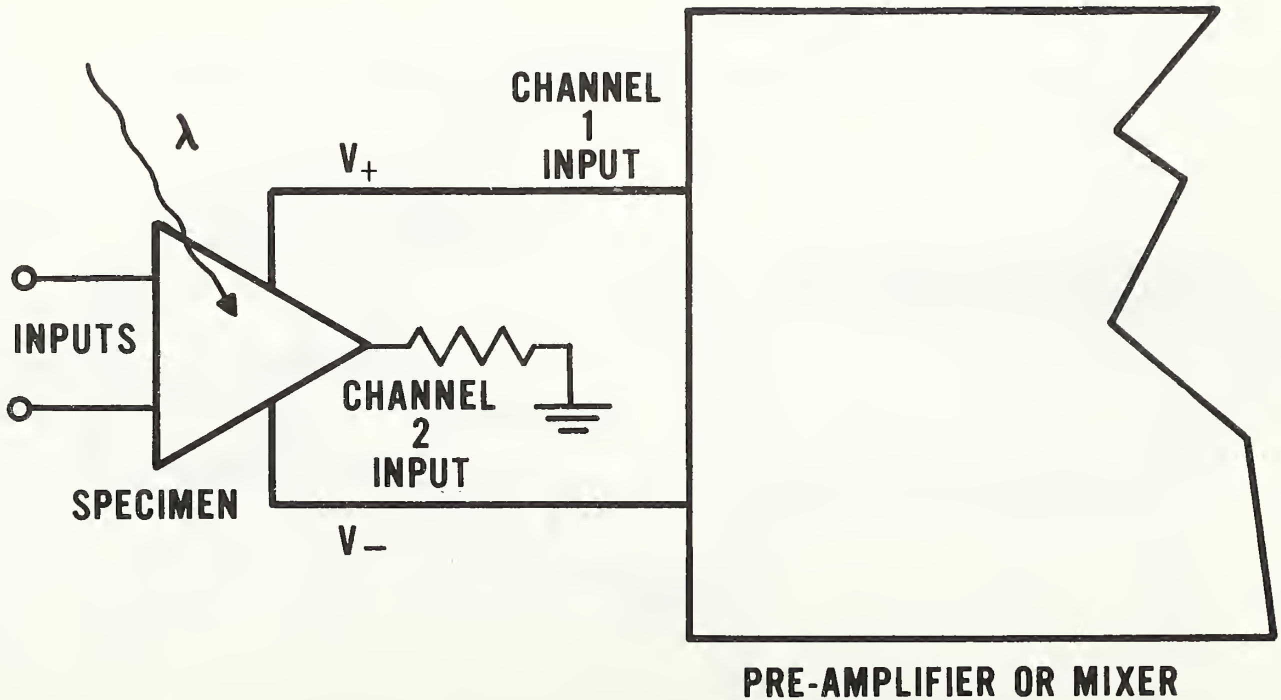


Figure 9. Hookup of an integrated circuit specimen when the circuit requires two power supplies.

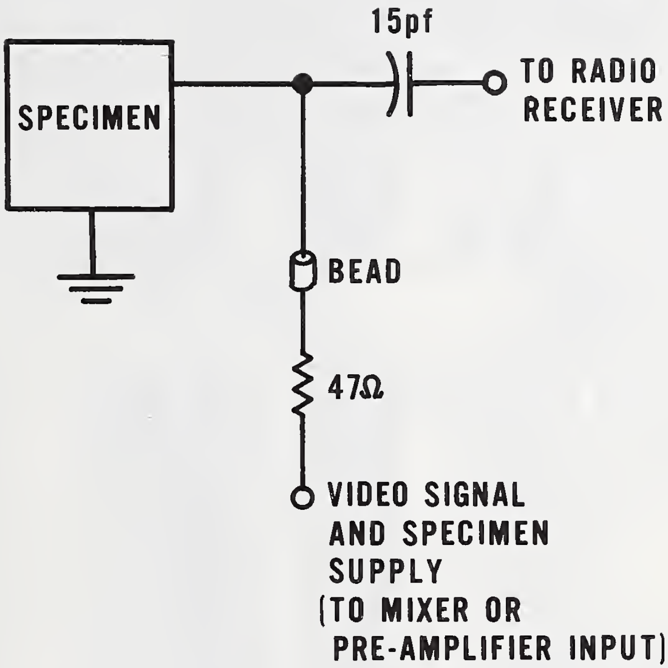


Figure 10. Specimen connection to both radio receiver and scanner's electronics.

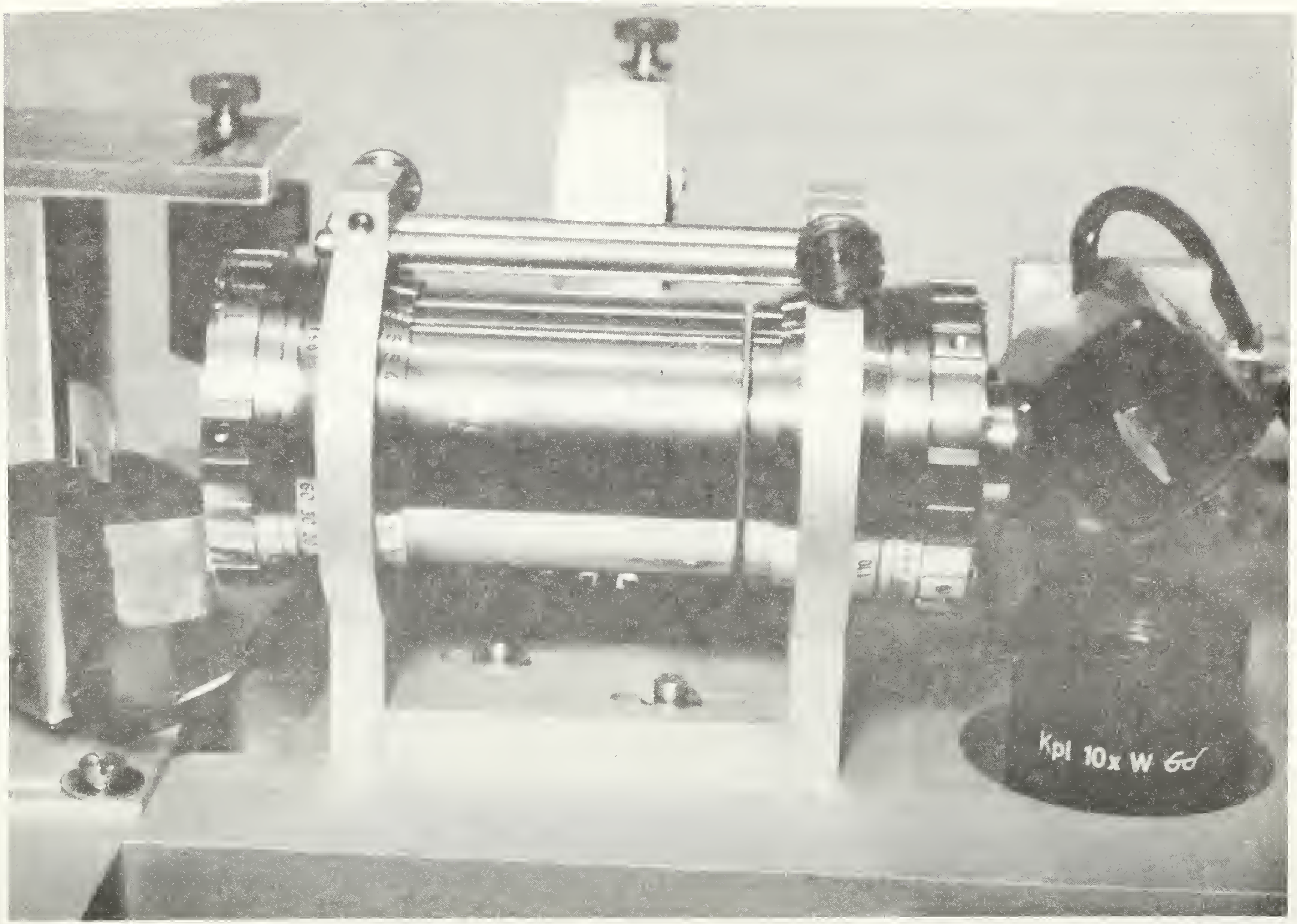


Figure B-1. Reimaging lens system L1.

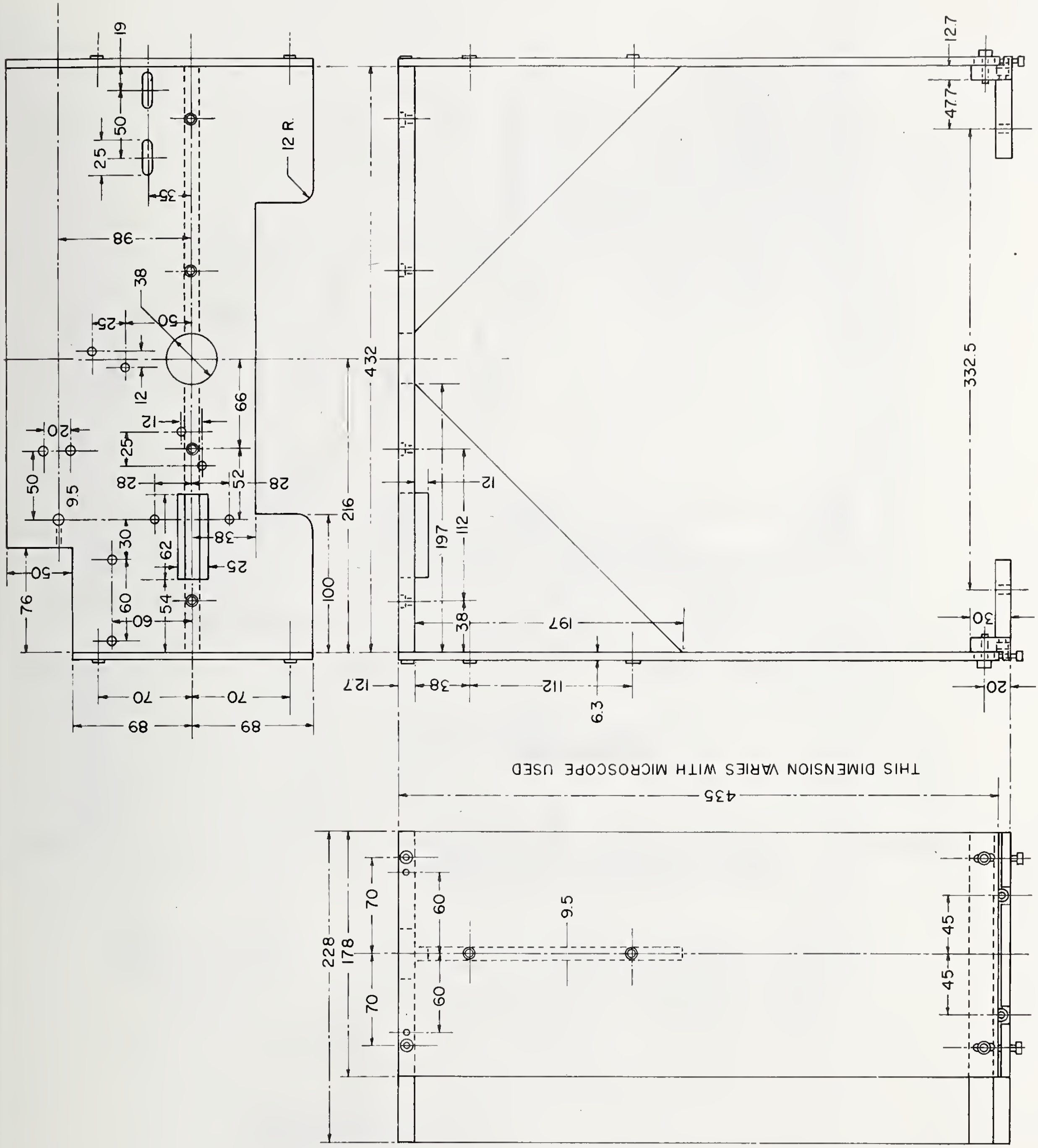


Figure C-1. Mechanical drawing of the support frame. Dimensions are given in millimeters.

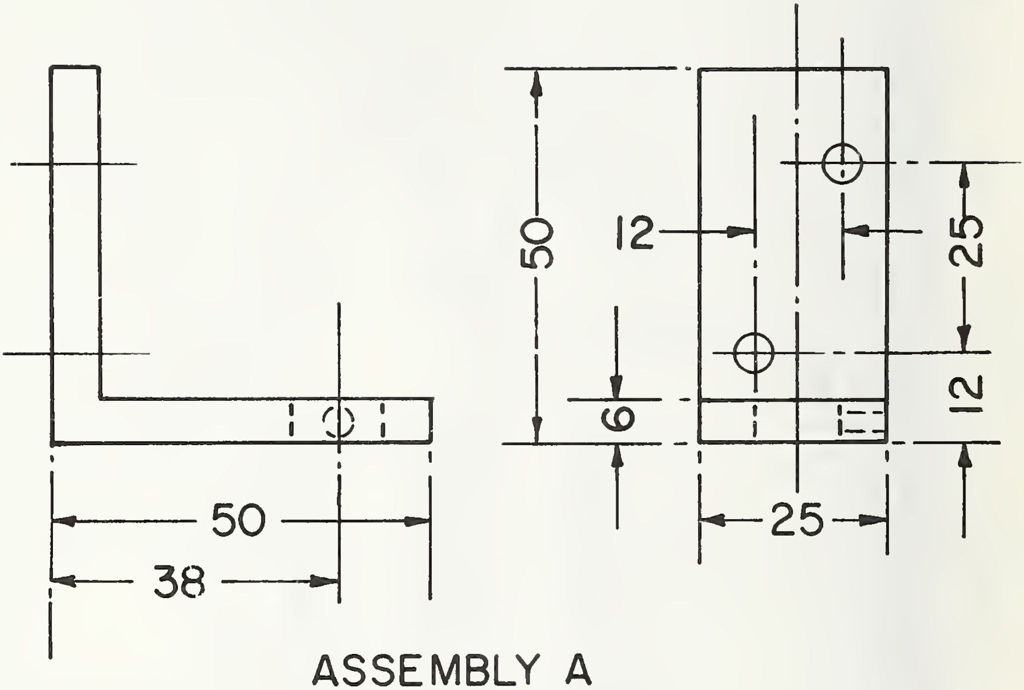


Figure C-2. The holder for the horizontal scanning mirror H. Dimensions are given in millimeters.

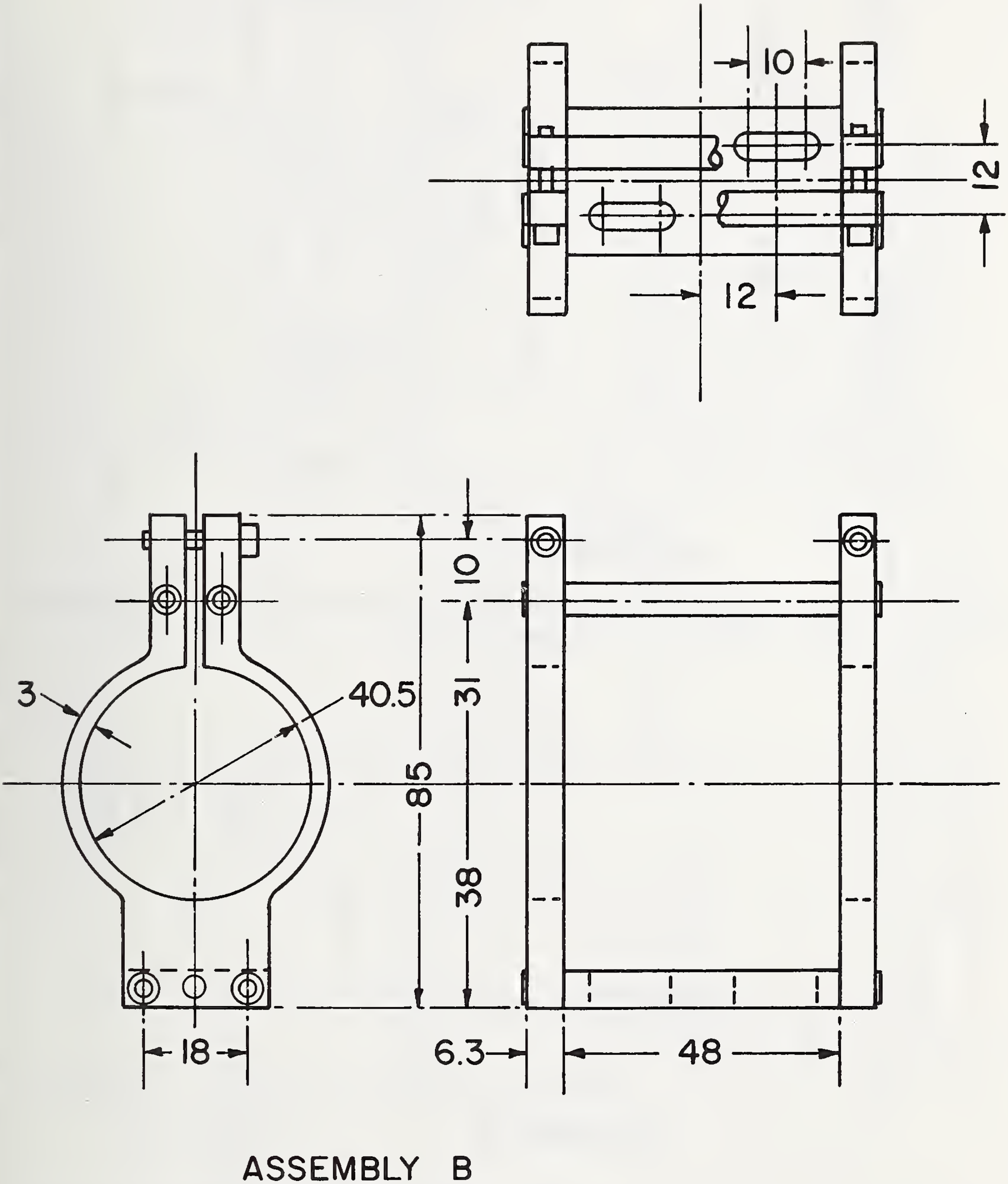
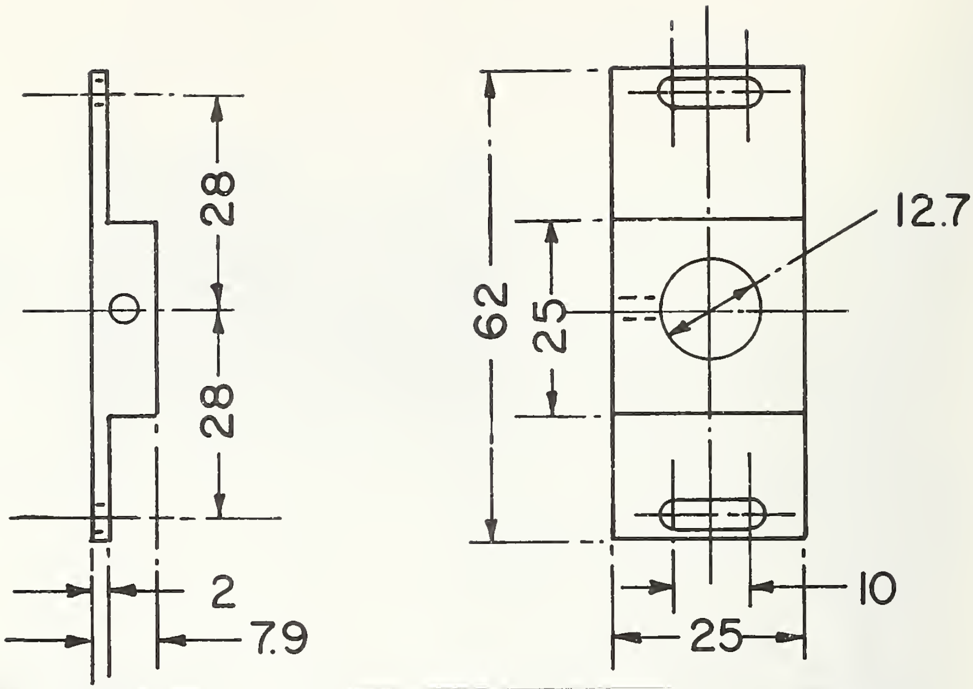
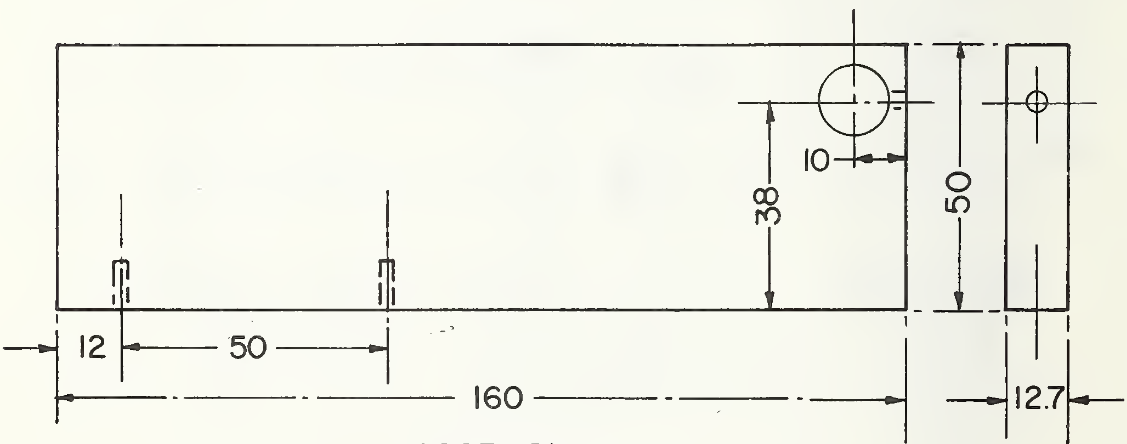


Figure C-3. The holder for the two lenses making up the L1 system. Dimensions are given in millimeters.



ASSEMBLY C

Figure C-4. The holder for the vertical scanning mirror V. Dimensions are given in millimeters.



ASSEMBLY D

Figure C-5. The bracket for holding mirror M1. Dimensions are given in millimeters.

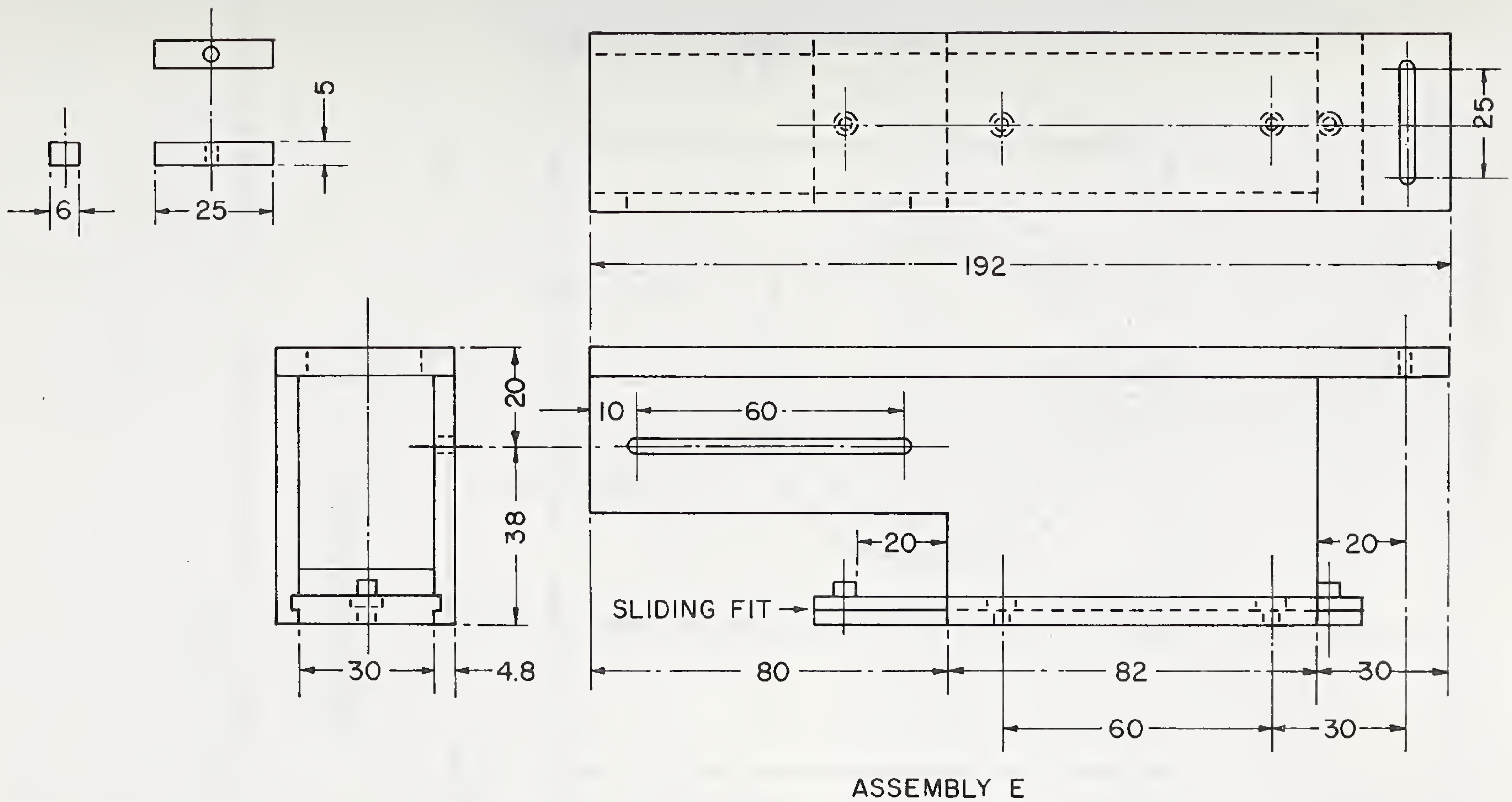
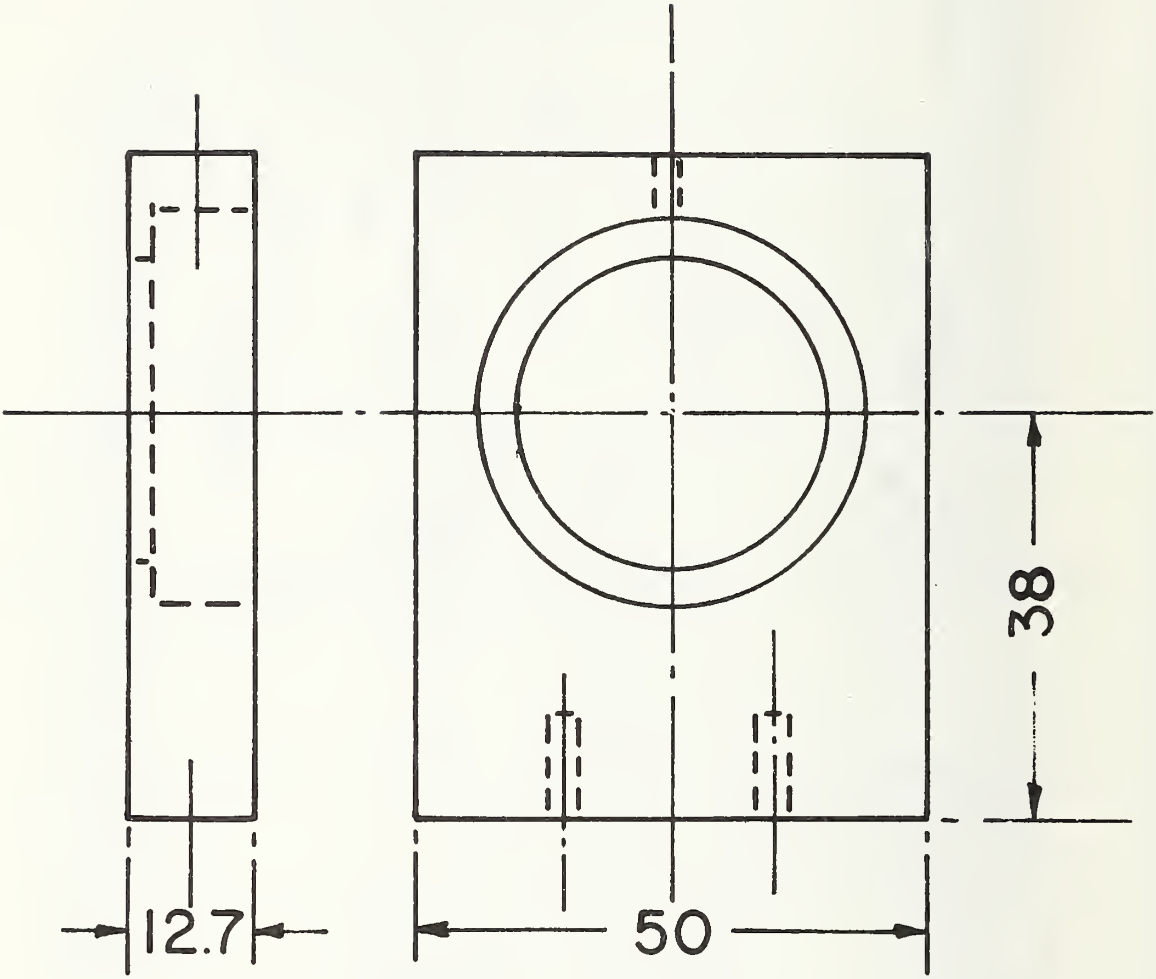


Figure C-6. The moveable slide which holds mirrors M3 and M4. The small item in the upper left is one of two identical mirror mounts which are held inside the slide with thumb screws. Dimensions are given in millimeters.



ASSEMBLY F

Figure C-7. The holder for the half wave plate. The dimensions are given in millimeters.

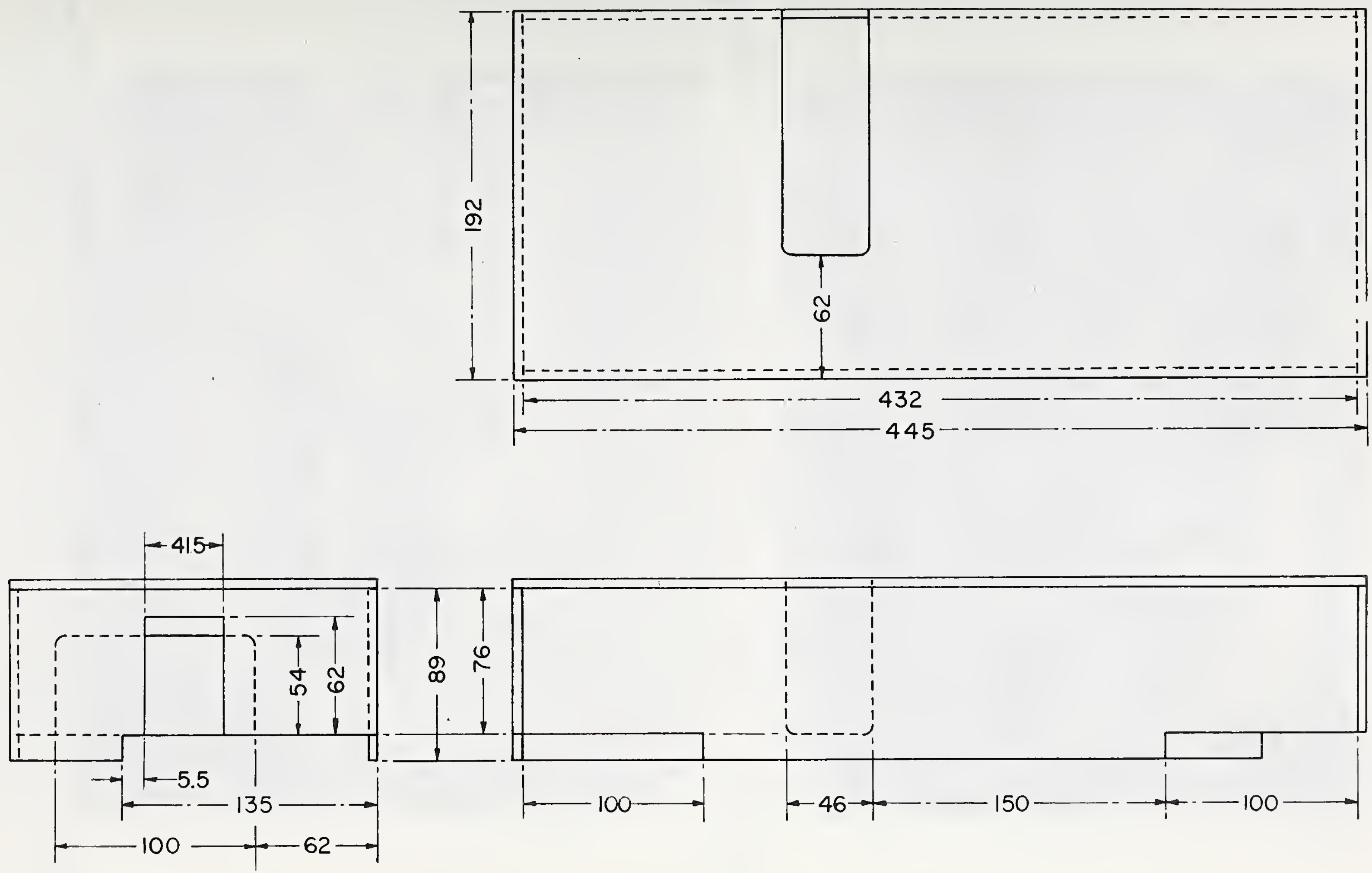


Figure C-8. The plexiglas dust cover. Dimensions are given in millimeters.

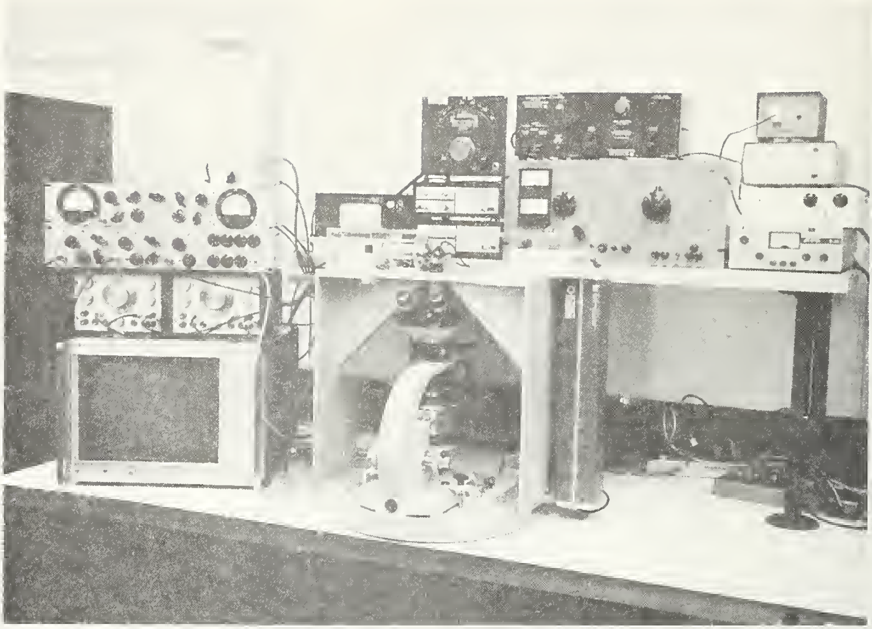


Figure C-9. Overall view of the laser scanner.

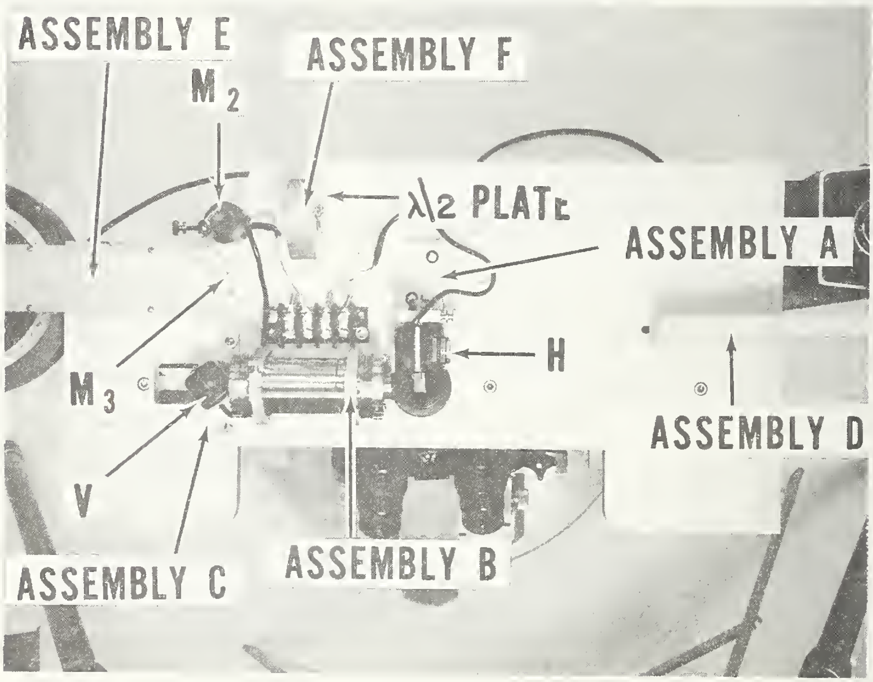


Figure C-10. Top view of the scanner showing the relative position of most of the optical components and assemblies.

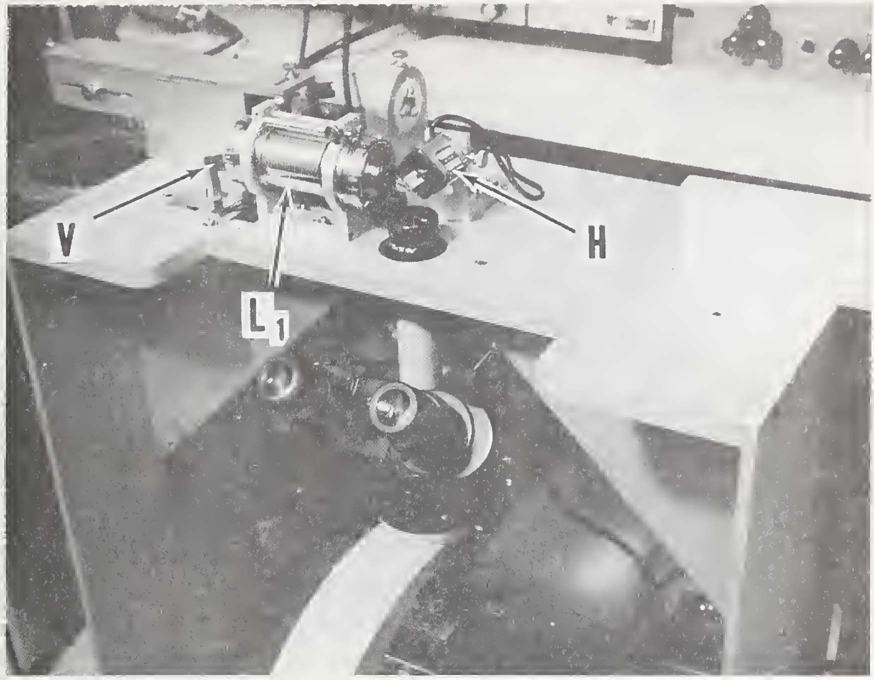


Figure C-11. Closeup of the optical deflection system. Note that the microscope camera tube extends through a hole in the support frame.

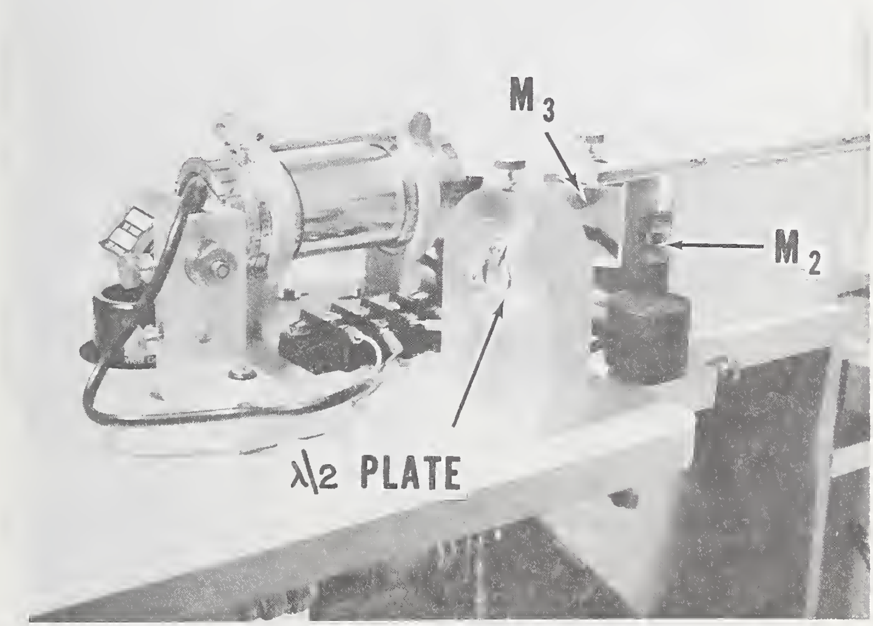


Figure C-12. Rear view of the support frame top.

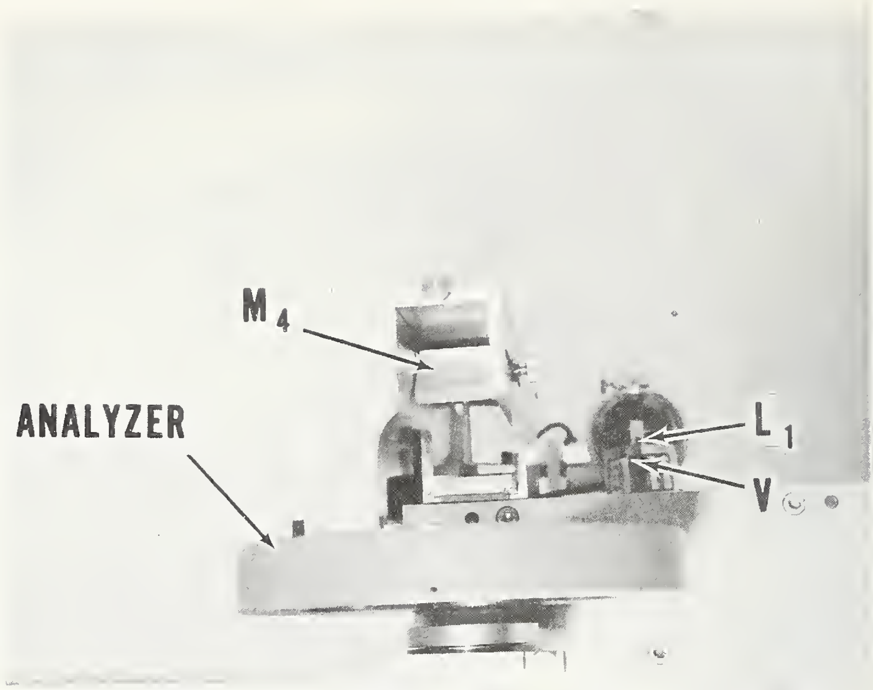


Figure C-13. End view of the top of the scanner as seen from the left.

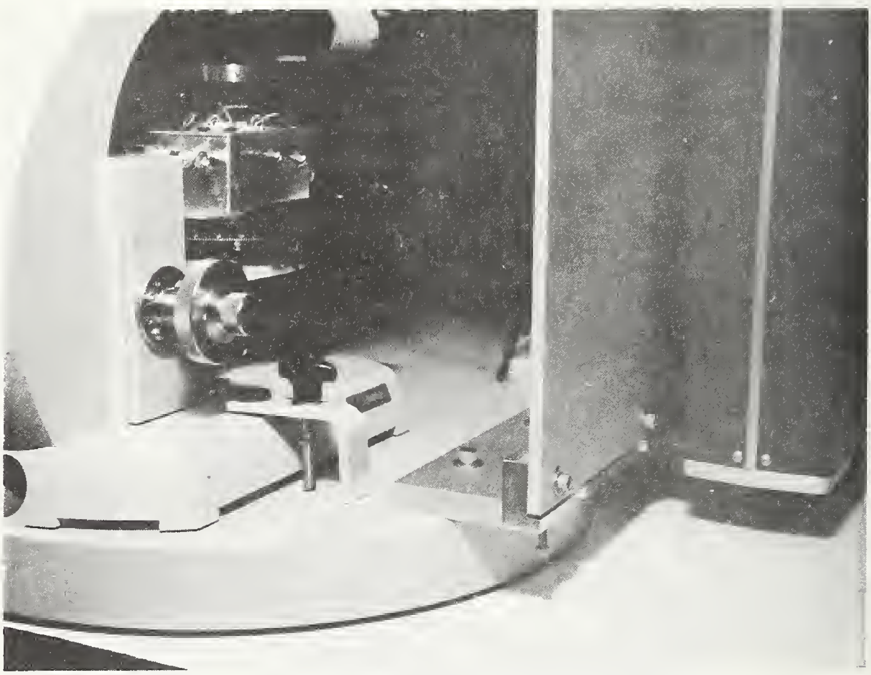


Figure C-14. The base of the microscope with the scanner support frame. The adjustment screws for moving the frame are visible.

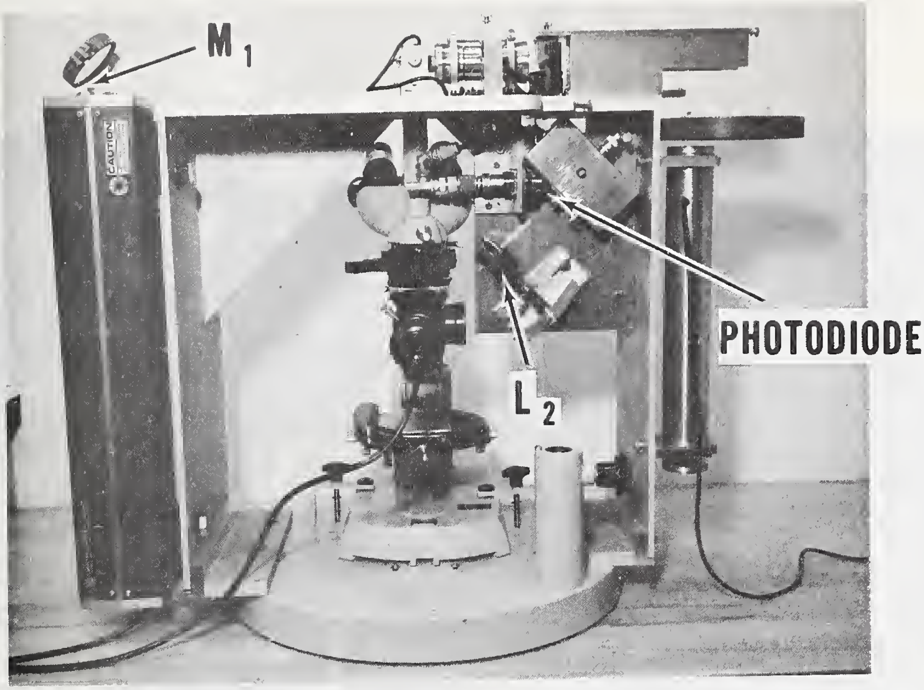


Figure C-15. Rear view of the scanner.

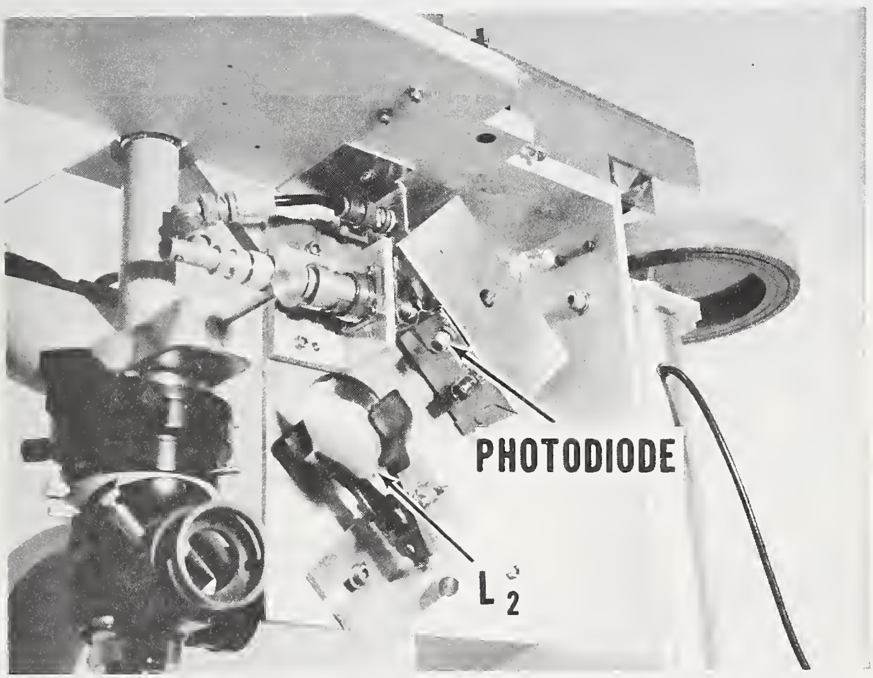


Figure C-16. Closeup of the reflected light circuit components.

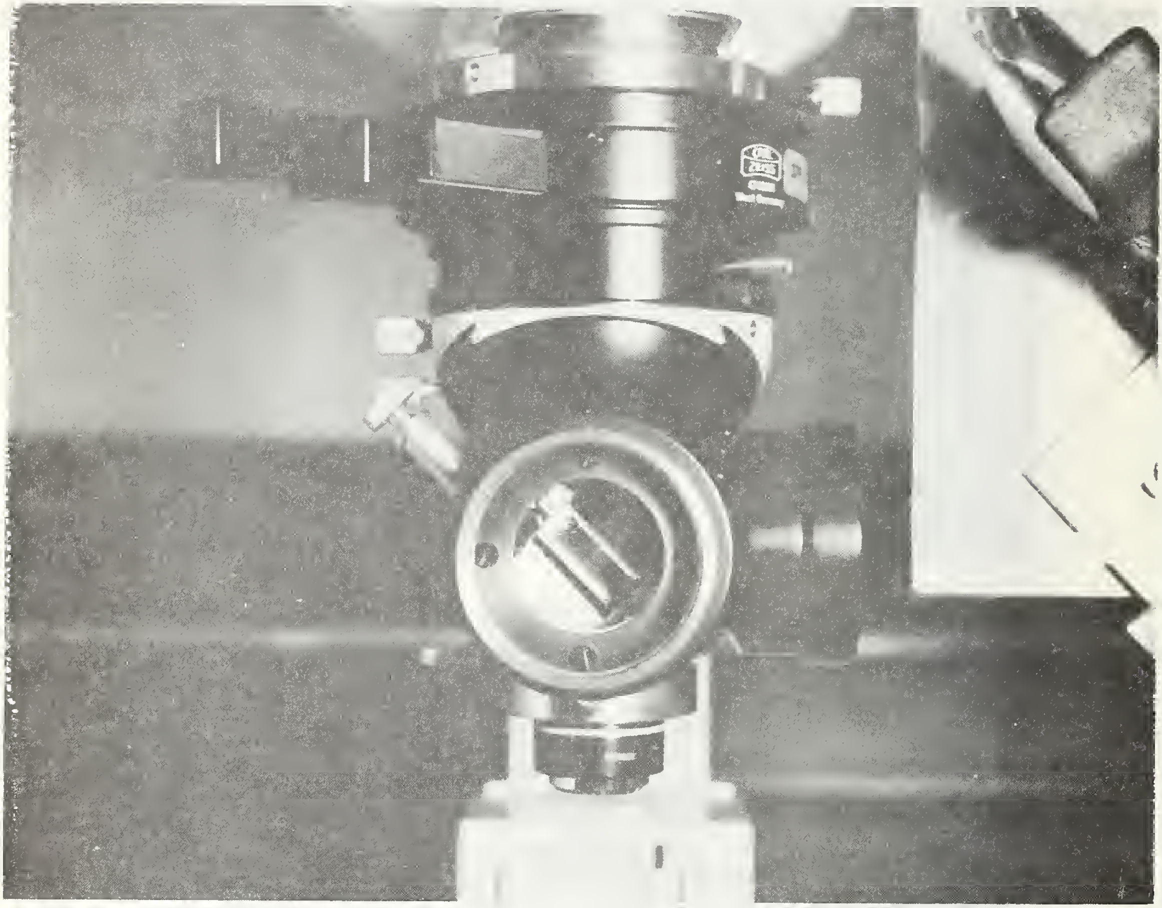


Figure C-17. The half silvered mirror in the microscope vertical illuminator port.

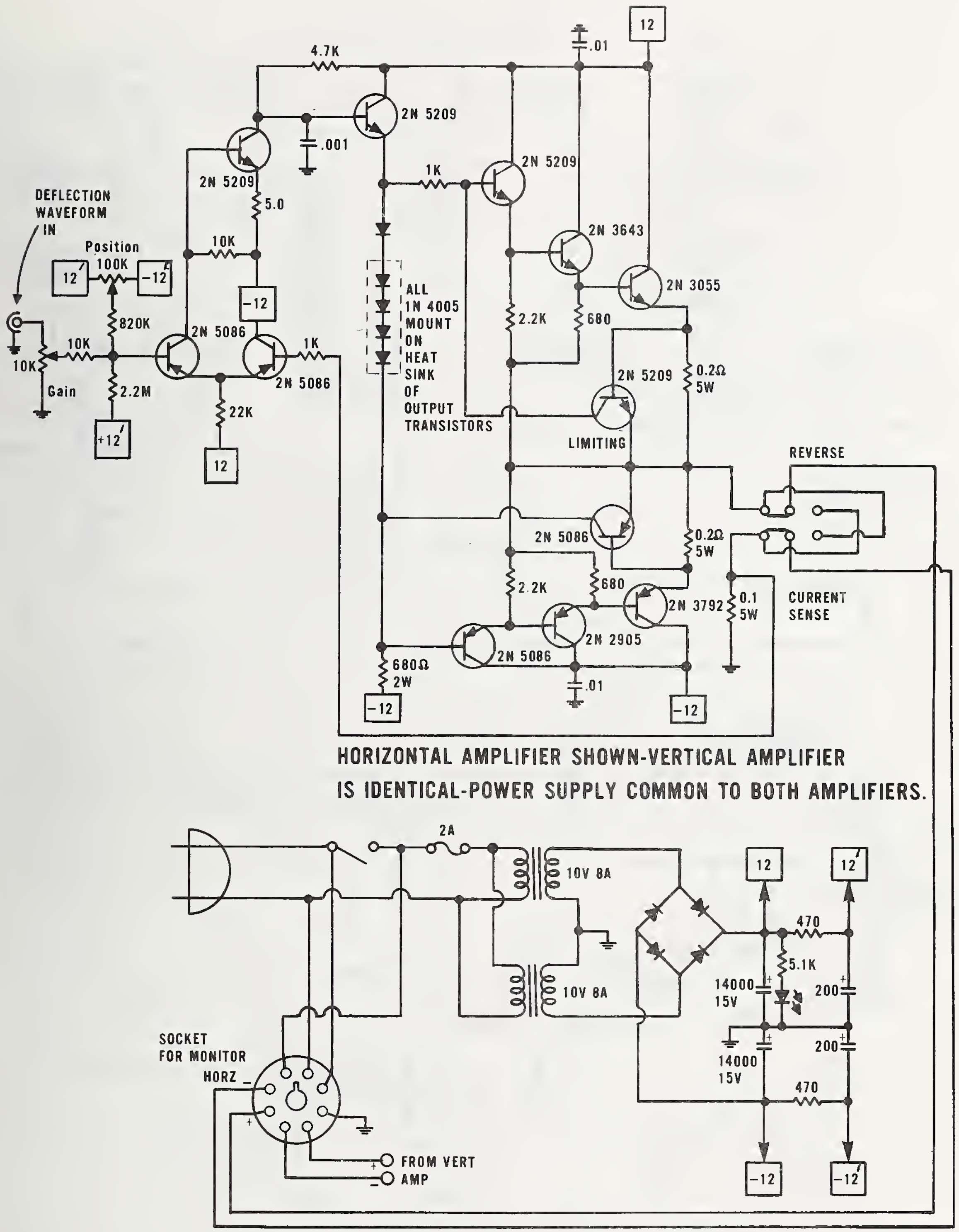


Figure D-1. Schematic diagram for one of two deflection amplifiers with power supply for the color monitor.

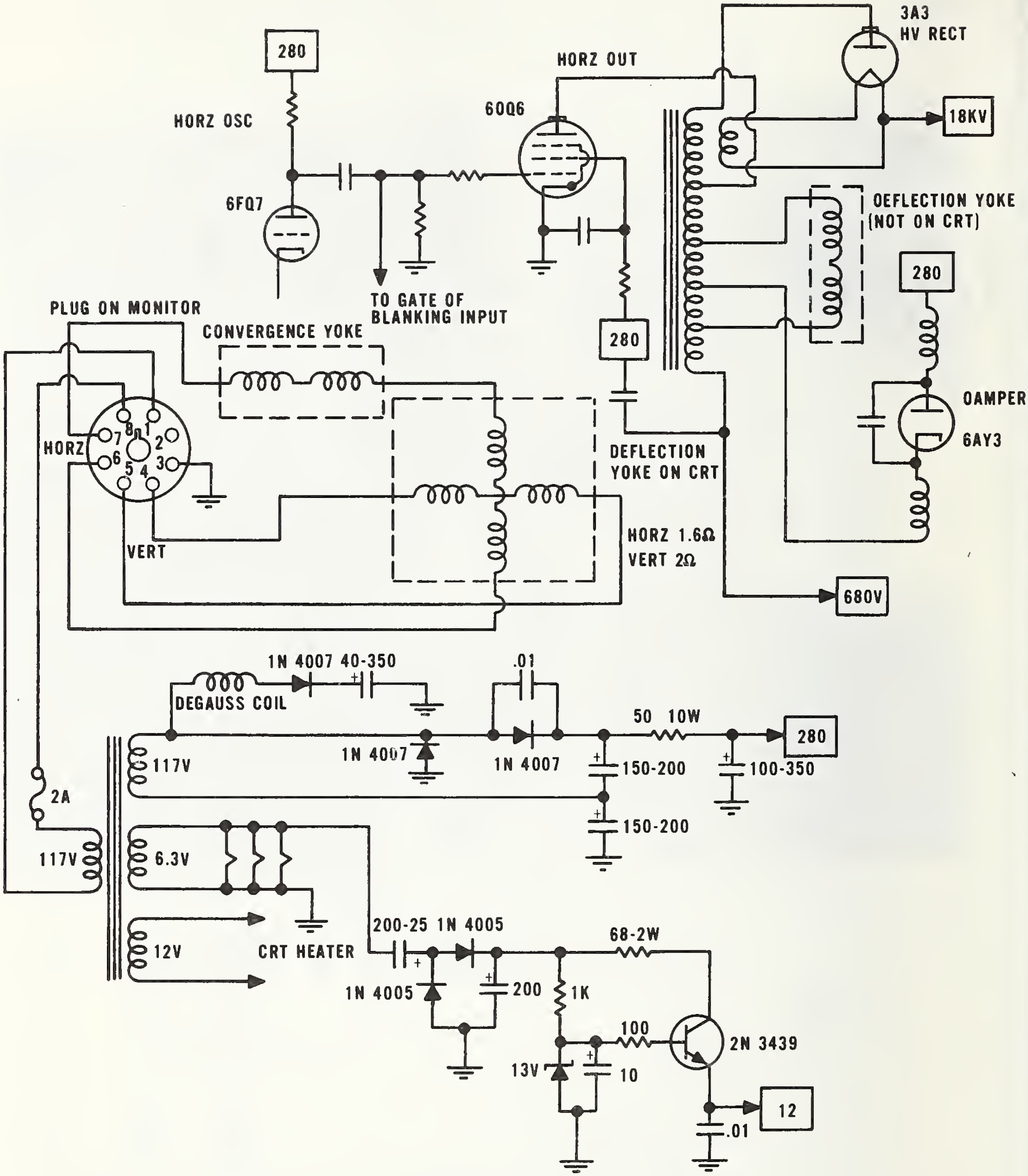


Figure D-2. Simplified schematic of high voltage portion of color monitor.

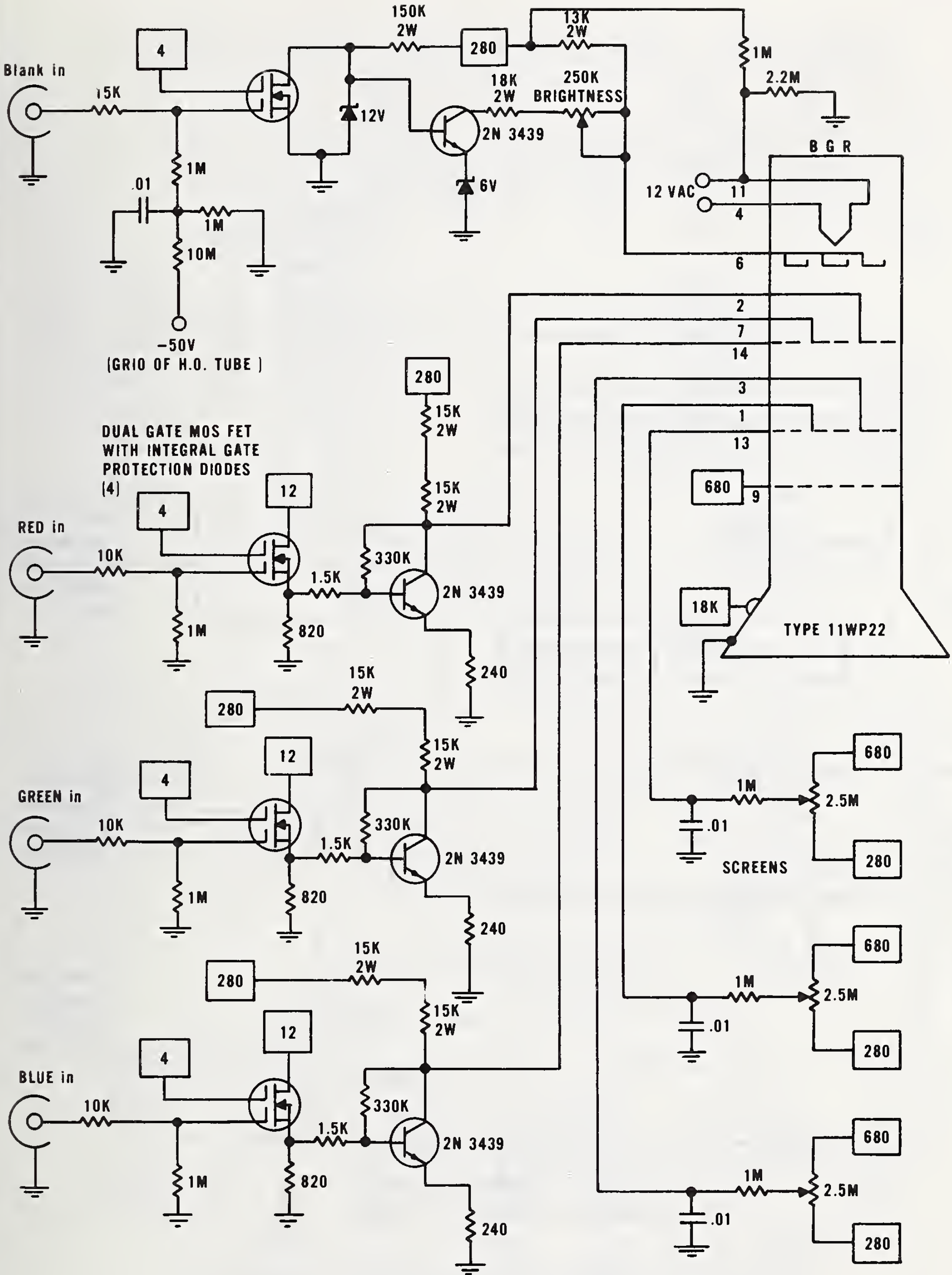


Figure D-3. Schematic diagram of the video and blanking circuits for the color monitor.

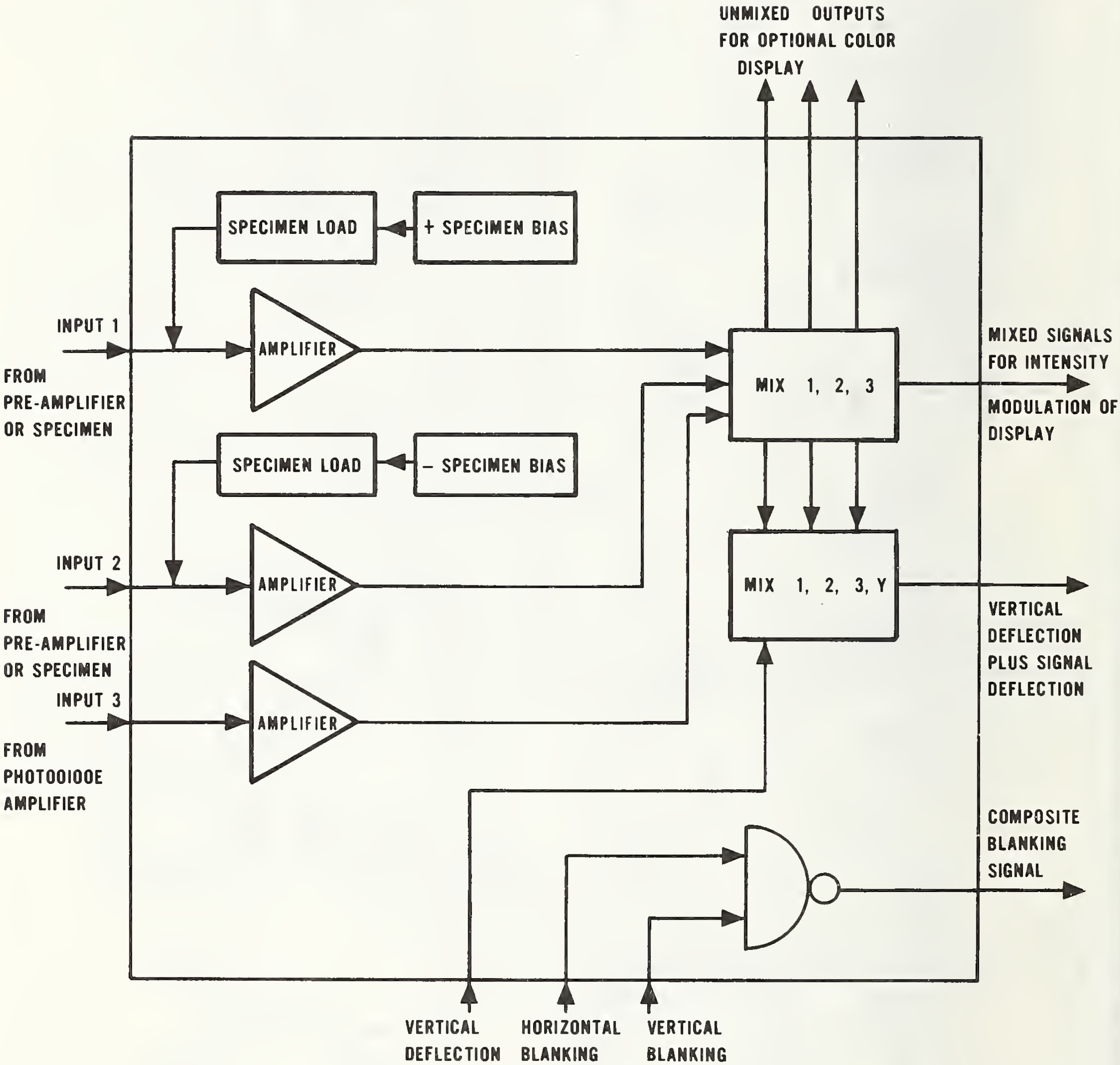


Figure E-1. Block diagram of mixer chassis.

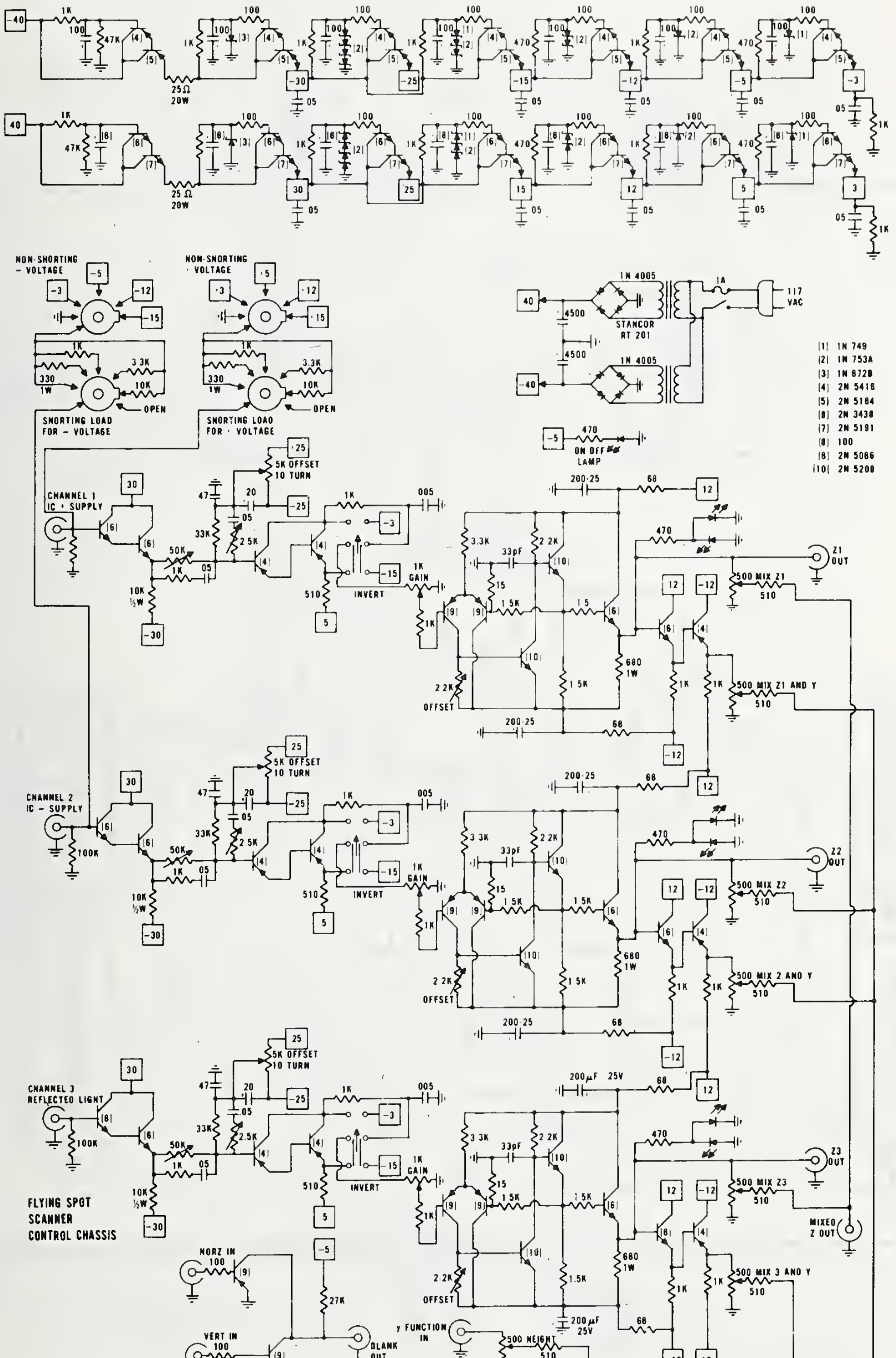


Figure E-2. Schematic diagram of the mixer chassis.

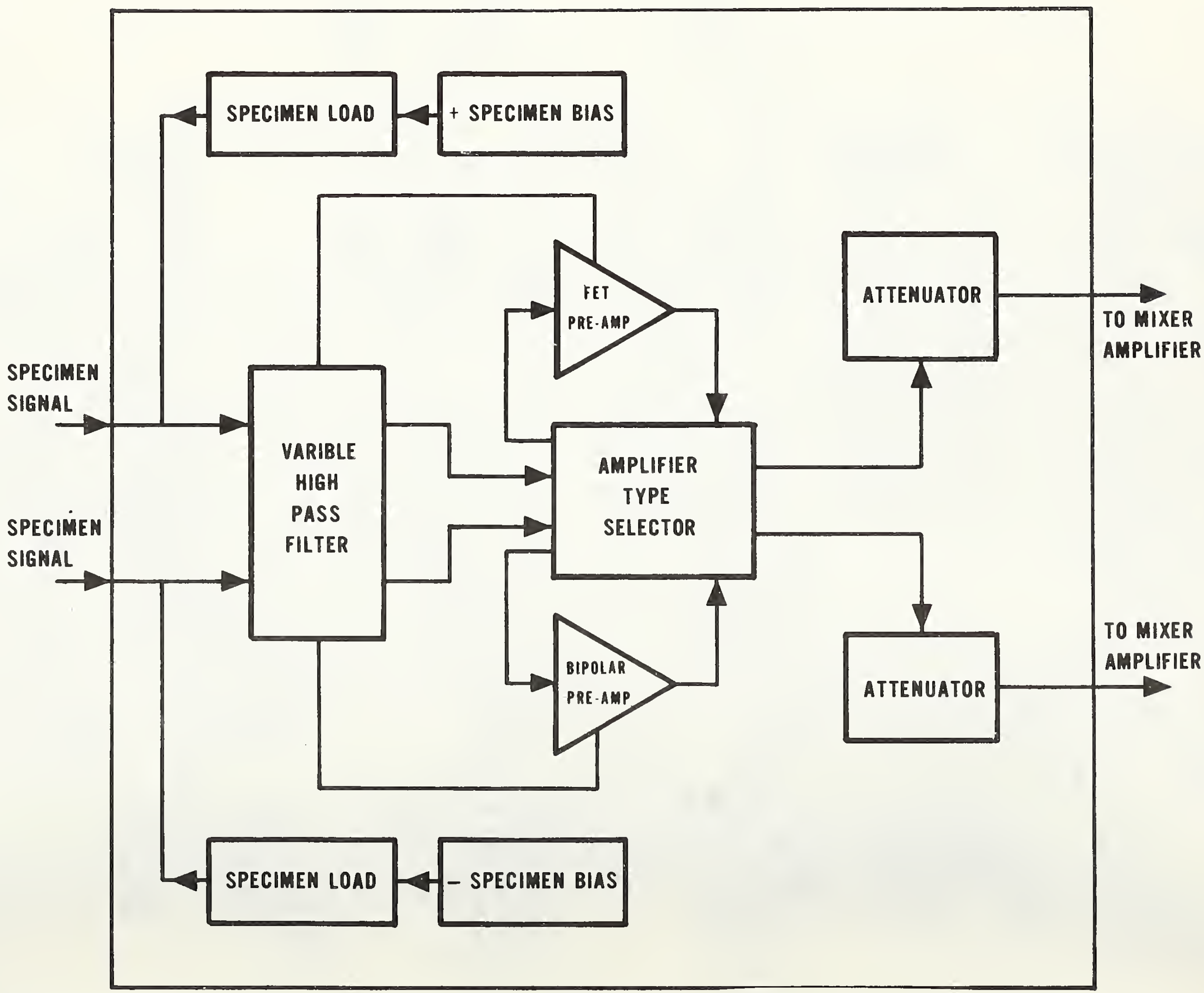


Figure E-3. Block diagram of pre-amplifier chassis.

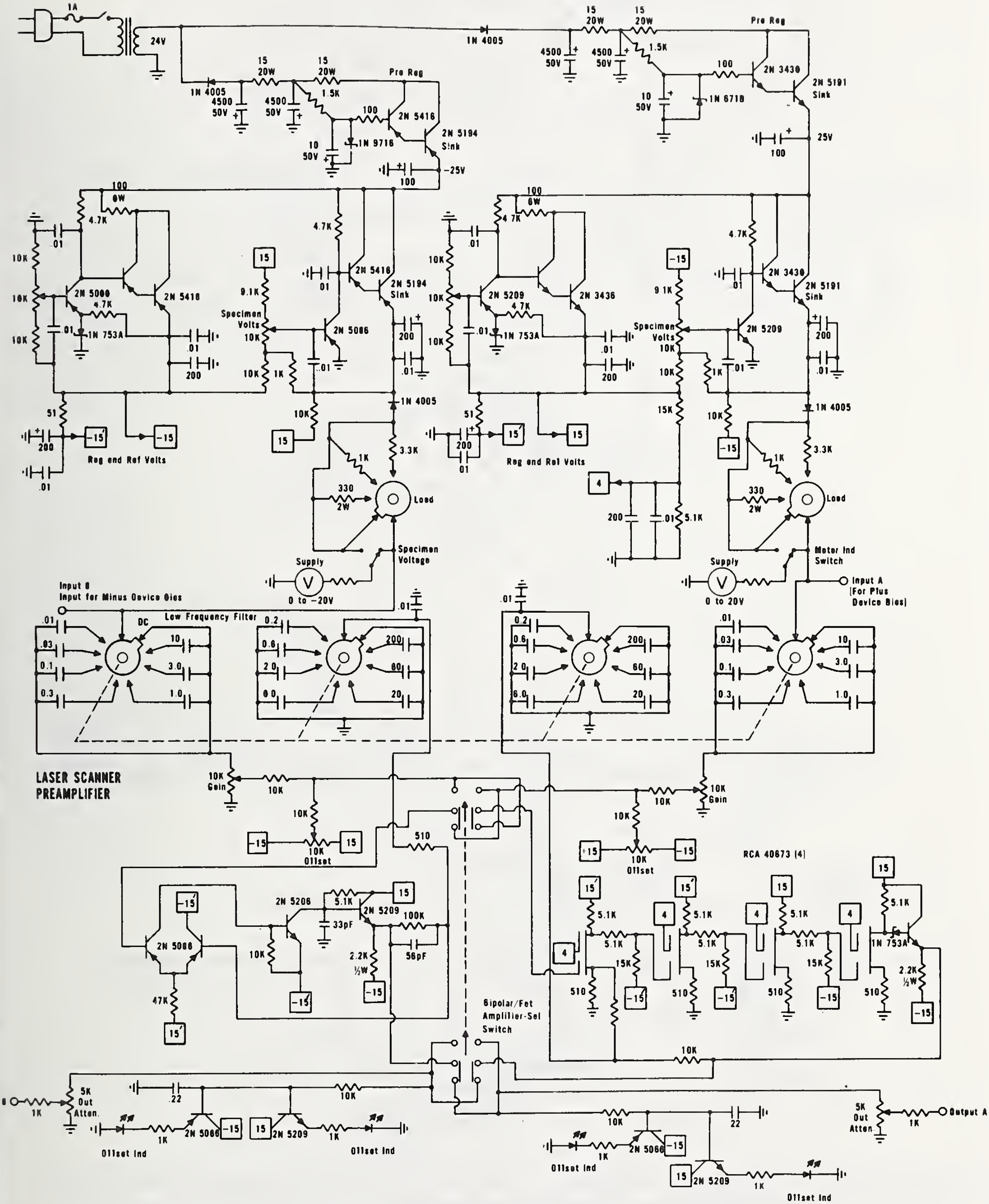


Figure E-4. Schematic diagram of the pre-amplifier.

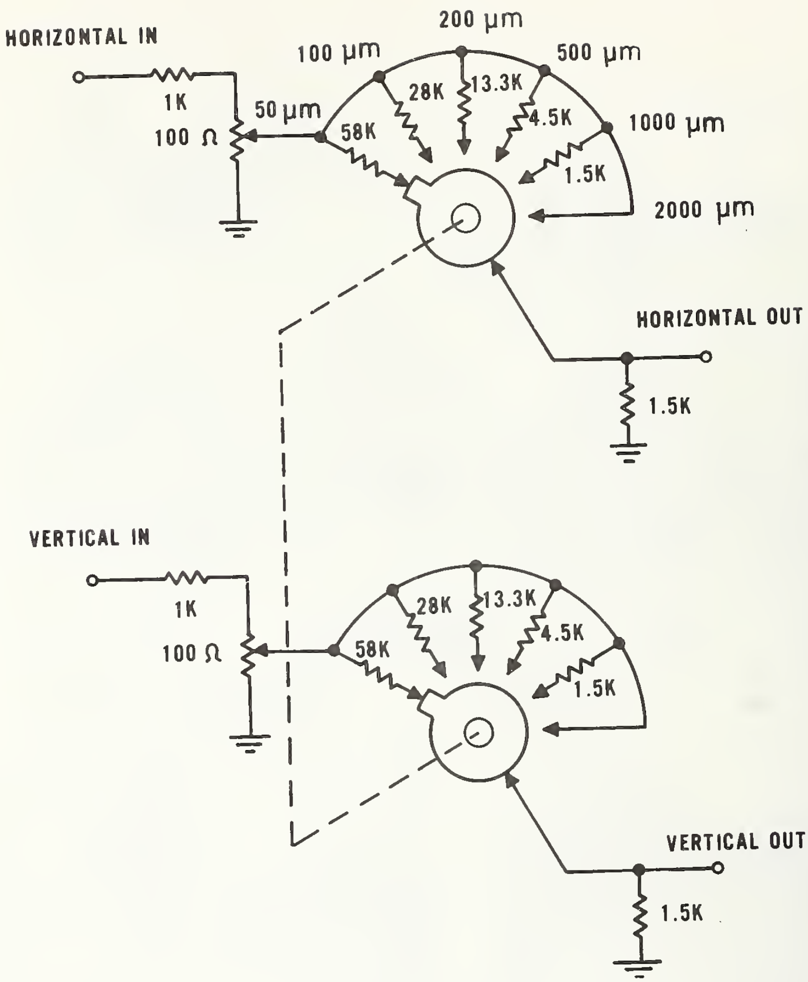


Figure E-5. Schematic diagram of the attenuator-magnifier.

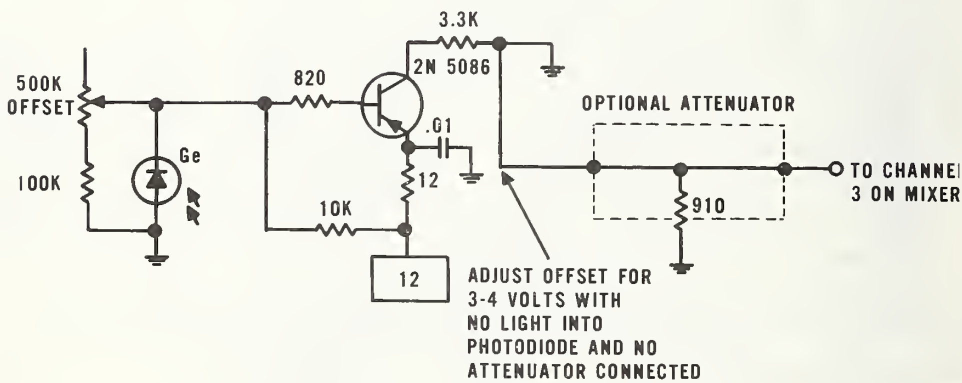


Figure E-6. Schematic diagram of the reflected light amplifier including the germanium photodetector.

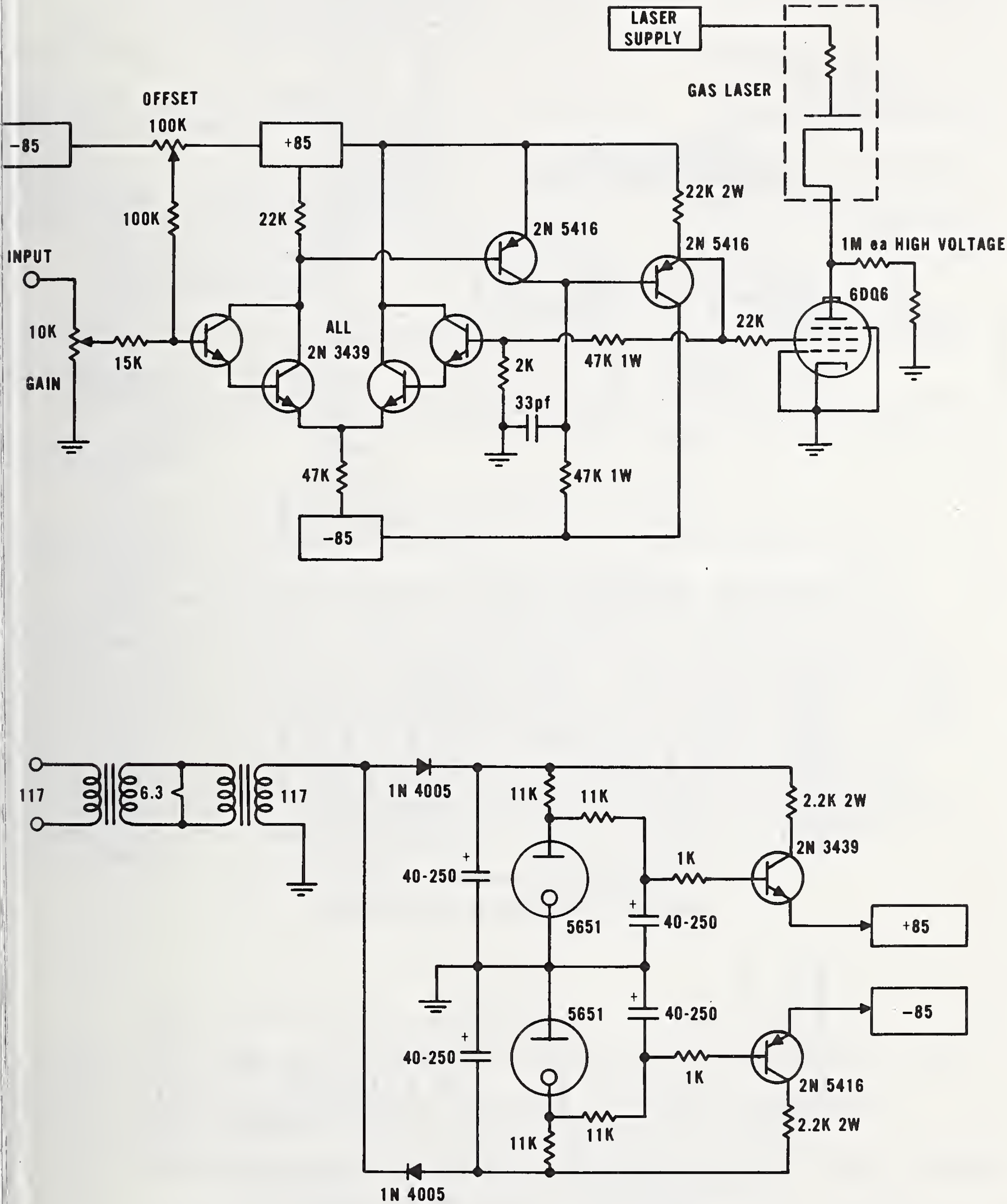


Figure E-7. Schematic diagram for the laser modulator.

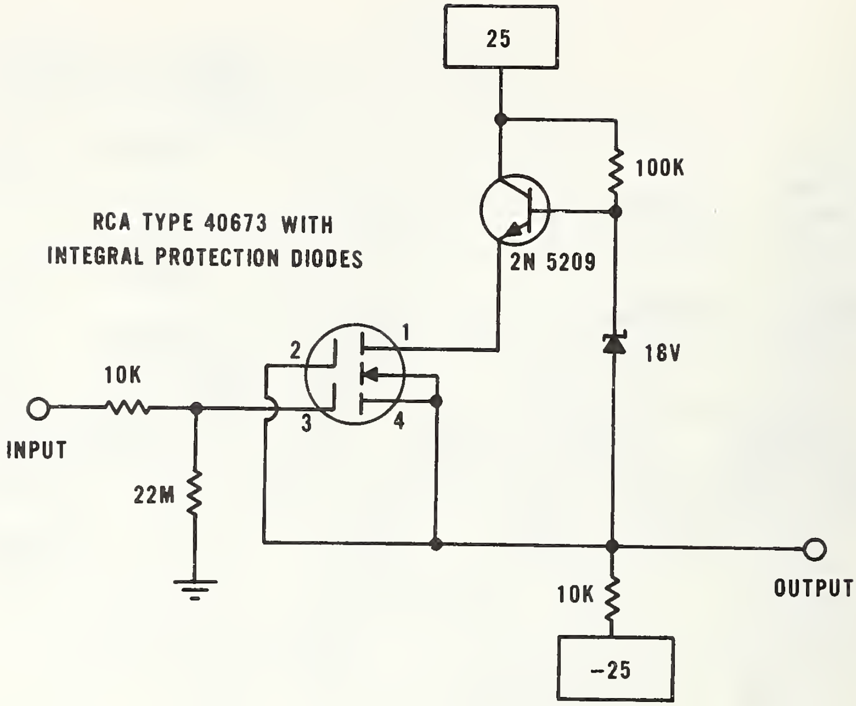


Figure E-8. Schematic diagram for the high impedance probe.

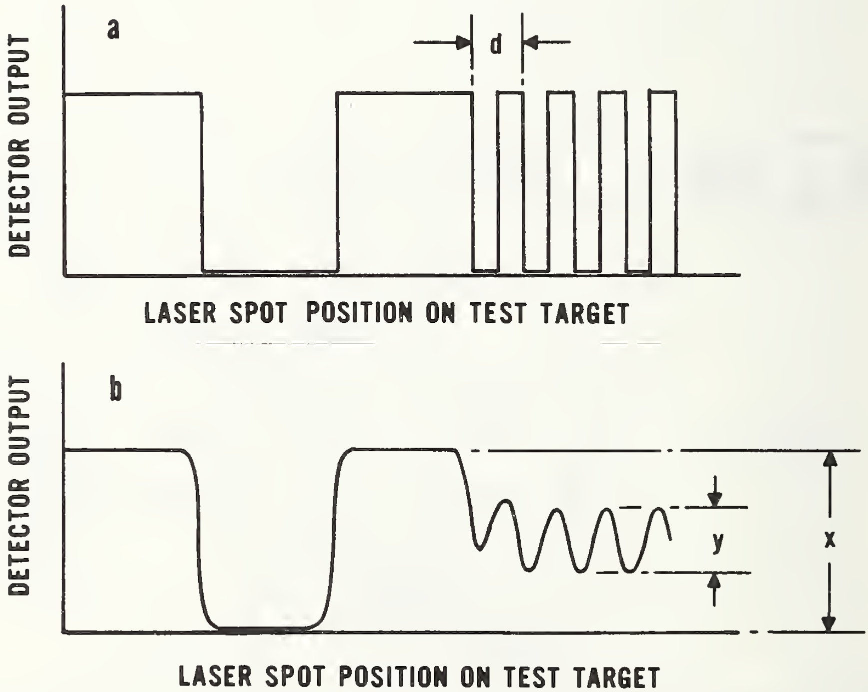


Figure F-1. Graphical explanation of the meaning of resolution figures quoted in the specifications section of this report.

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16. ABSTRACT *(A 200-word or less factual summary of most significant information. If document includes a significant bibliography or literature survey, mention it here.)*

This is a construction guide and operators manual for a laser scanner built for semiconductor device studies. A very brief discussion of the theory of operation of the scanner is given. The scanner's operation from a systems point of view is described in detail with emphasis on block diagrams. The scanner is described from a hardware point of view with a detailed description of the function of the various controls on the electronic equipment that was built for the laser scanner. A quick guide for the use of the scanner is given so that a person unfamiliar with the instrument can use it effectively. Specifications relating to the scanner's data gathering ability are also given. Mechanical drawings and circuit schematics are given to enable others to build a similar scanner. The optics and their alignment are discussed. Various display modes including color are discussed to enhance operator viewing.

17. KEY WORDS *(six to twelve entries; alphabetical order; capitalize only the first letter of the first key word unless a proper name; separated by semicolons)*

Electronic reliability, electronics; laser scanner; measurement method; mixer; optics; pre-amplifier; radio receiver; semiconductor device studies.

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