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Intensified CCD for Ultrafast Diagnostics

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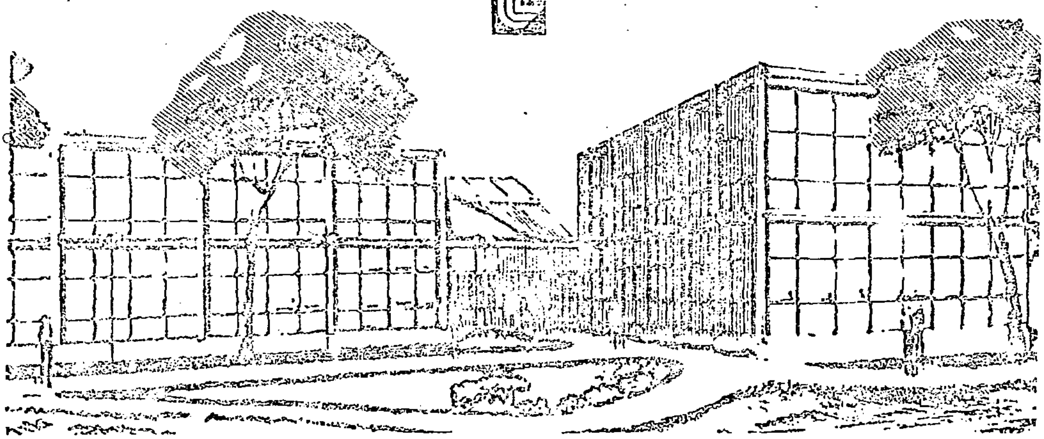

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Intensified CCD for Ultrafast Diagnostics*

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Abstract

Many of the present laser fusion diagnostics are recorded on either ultrafast streak cameras or on oscilloscopes. For those experiments in which a large volume of data is accumulated, direct computer processing of the information becomes important. We describe an approach which uses a RCA 52501 back-thinned CCD sensor to obtain direct electron read-outs for both the streak camera and the CRT. Performance of the 100 GHz streak camera and the 4 GHz CRT are presented. Design parameters and computer interfacing for both systems are described in detail.

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I. INTRODUCTION

Many present laser fusion diagnostics,[1] such as measurements of the laser beam, X-ray, neutron and alpha intensity vs time are recorded using either an ultrafast electronic streak camera or a wide bandwidth oscilloscope. The temporal resolution of these instruments ranges from the order of ten picoseconds for the optical and the X-ray streak cameras to a few nanoseconds for a neutron time-of-flight detector and recording system. A characteristic of most laser fusion experiments is the generation of a very large volume of data due to the many parameters that are simultaneously monitored. To perform these experiments quickly and efficiently, a diagnostic instrument used for laser fusion should be able to interface directly with a central computer, whereby direct data processing by the computer can be implemented.

The motivation behind the work described in this paper is based on the need to directly computerize existing laser fusion diagnostic instruments. The approach we have chosen is to use a back-thinned RCA 52501 charge-coupled device (CCD) to replace the normal phosphor in both an ultrafast streak tube and a wide bandwith cathode ray tube (CRT). The CCD is used to directly image the electrons generated by the respective instruments.

II. RCA 52501 CCD CHARACTERISTICS

It is important to determine the characteristics of the sensor in the mode in which the device is required to operate. For both the CRT and the streak camera instruments, the CCD sensor is used as a direct electron imager. The electron excitation time per CCD pixel ranges from a dc illumination condition during setup down to about ten picoseconds per pixel during actual data taking.

Figure 1a shows the response of a back-thinned (∿ 10 μm thick) and back e-beam illuminated RCA 52501 CCD to 4, 5 and 6 keV energy electrons. For the case of the ultrafast streak[2] camera, the desired information is contained in the form of an intensity vs position profile. It is therefore necessary to determine whether the CCD sensor is linear (i.e. $\gamma = 1$) to input electron excitation and furthermore, to verify that this linearity is maintained when the input electron pulse duration is reduced to the picosecond range (i.e. reciprocity is preserved).

Although the CCD data shown in Fig. 1a is derived using electron pulses in the microsecond range, similar experiments were performed using a 50 ps 1.06 μm coherent light source. If the assumption that the CCD is insensitive to the manner in which the electrons are produced is valid, then it can be concluded that the RCA 52501 CCD is linear to electron excitation and its reciprocity is maintained down to at least the 50 ps range. It should also be noted, however, that not all the CCD sensors have this desirable reciprocity property. For example, the Fairchild 202 CCD is linear in the dc illumination mode (i.e. $\gamma = 1$), but the sensor has a transfer function gamma value of 1.3 when a 50 picosecond light pulse is used. The deviation in sensor linearity was observed in all of the 202 and 211 CCDs tested. Since the RCA and Fairchild CCDs differ both in the chip's construction (i.e. surface vs buried channel) and in its architecture (i.e. frame vs interline transfer), it was not clear if either difference was the cause of the reciprocity failure. To help answer this question, we have obtained some preliminary data on the reciprocity behavior of an experimental RCA all buried channel CCD. Initial analysis indicates that both the RCA and Fairchild all buried channel CCDs exhibited reciprocity failure in the tens of picosecond time domain. No adequate theory has been forwarded to even suggest that the buried channel structure is responsible for the reciprocity failure. If indeed the buried channel device exhibits this reciprocity failure, then buried channel CCD sensor may not be applicable for ultrafast diagnostics.

In most ultrafast diagnostics, such as a 10 ps resolution streak camera or a 4 GHz CRT, some form of signal amplification is required to bring the output to a usable level. In the conventional case, where a phosphor is used to image the electrons, an optical or electron image intensifier, such as a microchannel plate, is used to increase the light output from the phosphor to a level suitable for film recording. In our case where the CCD is used in place of the phosphor, signal amplification is obtained by direct electron multiplication within the silicon. The CCD gain (G) can be calculated at room temperature by:

$$G = \left[\frac{E_{in} - E_{dead}}{3.66}\right] , \qquad \text{Eq. 1}$$

Where E_{in} is the incident electron energy and E_{dead} is the CCD back layer dead energy in eV. Figure 1b shows the CCD gain vs input electron energy result for the RCA 52501 CCD. Details of the technique used for the gain measurement are given elsewhere.[3] For comparison, a plot of the ideal gain curve is also shown where the E_{dead} energy in Eq. 1 is set equal to zero. Data for a Fairchild 202 CCD is also shown.

Typically for a S-1 photocathode streak camera when operating at a streak speed of 35 ps per mm, the maximum number of photoelectrons that each CCD pixel (30 μm x 30 μm) receives is on the order of 10^3 electrons. For the present RCA 52501 CCD, the full well capacity is between 5×10^5 to 1×10^6 electrons. Using these values, the CCD electron gain required for an ultrafast streak camera is between five hundred to one thousand. From Fig. 1b, this CCD gain value corresponds to an input electron energy of around 4 to 6 keV.

When the sensor is incorporated into an ultrafast CRT, the CCD output O_{CRT} in units of the number of electrons/pixel is given by:

$$O_{CRT} = 6.25 \times 10^{18} \cdot \left(\frac{E_{in} - E_{dead}}{3.66}\right)\left(i\right)\left(\frac{\Delta t}{N_{cell}}\right)\left(\frac{d_{cell}}{d_{spot}}\right)^2$$

Eq. 2

Where E_{in} and E_{dead} again are the input electron energy and the CCD dead layer energy respectively. The CRT beam current is denoted by i, and Δt is the total time required to sweep the electron beam across N_{cell} number of CCD cells. The diameter of the electron beam is given by d_{spot} and the CCD cell size is denoted by d_{cell}.

Figure 1c gives the blooming characteristics of the RCA 52501 CCD using a continuous incoherent 1.06 μm light source. The vertical anti-blooming characteristics has been optimized by adjusting the RCA CCD image section voltage ($V_{\phi AL}$) of the nonstoring electrodes so that they are in the accumulation condition (i.e. $V_{bb} > V_{\phi AL}$). The voltage on the storing electrodes ($V_{\phi AH}$) is arranged so as to obtain, during light integration, a well size in the image area smaller than or equal to any subsequent wells encountered in the A→B, B→C and C→output charge transfer process.

Although the CCD blooming data given in Fig. 1c was obtained using photon illumination, similar qualitative experiments were also performed using electrons as the input excitation source. We have verified that the general CCD blooming characteristics are similar in either the electron-in or photon-in mode. These experiments tend to verify that CCD behavior, in most cases, is source-independent.

A good anti-blooming property is important in instruments such as a streak camera where severe localized sensor saturation can occur. With this anti-blooming characteristic, those portions of the streak data that are in close proximity to the highly saturated data will not be destroyed by the vertical blooming associated with many present CCD sensors.

The practicality of an intensified CCD instrument depends greatly on the useful lifetime of the sensor in the electron beam environment. The damage mechanism for a front e-beam illuminated CCD is well documented.[4] Briefly, this electron damage is induced by a non-uniform accumulation of positive charges in the SiO_2 insulator. This positive charge build-up is due to a difference in the electron and hole mobilities in SiO_2 while under the influence of the E-fields generated by the normal operation of the CCD. For the backside e-beam illumination case, the problem of the direct electron/hole pair production in the SiO_2 layer induced by the incident electrons is eliminated, since the electrons are no longer required to transverse the SiO_2 layer before reaching the Si. However, CCD damage can still occur by the indirect creation of the electron/hole pairs in the SiO_2 insulator via the soft Bremsstrahlung X-rays that are generated when the electrons impact into the Si.

Fig. 1d shows the experimental results of two CCDs under e-beam illumination. Both CCDs were operated using incident electron energies so as to obtain full well CCD outputs with both sensors having electron gain of 1000. The electron pulse density was equal for both the RCA and Fairchild CCDs, and typically this density was around one electron per square μm. It is clear from Fig. 1d that the electron-induced damage due to the front e-beam illuminated CCD (Fairchild 202) is many orders of magnitude greater than the back-illuminated device (RCA 52501). Translating these CCD damage data into practical operating time durations, the Fairchild 202 CCD will exhibit noticeable damage within one minute of continuous electron exposure. In contrast, the RCA 52501 CCD yields no detectable sensor damage even after several weeks of continuous e-beam illumination. However, we assume, although not experimentally verified, that if the RCA 52501 CCD were illuminated from the front side, electron damage would occur in a time duration similar to the Fairchild 202 and 211 CCDs.

The vertical and horizontal spatial resolutions of the intensified CCD sensor are pertinent to both the streak camera and the CRT operations. Briefly, the ultrafast streak camera is used to measure the temporal light intensity profile of an event. The intensity vs time of the input light pulse is converted via the streak camera into intensity vs position on the CCD sensor. Basically, the streak camera can be viewed as an optical CRT in which the usual thermionic cathode is replaced by an optical photocathode and in which output intensity is recorded. In normal operation, an optical slit image is focussed onto the photocathode, and the resulting photoelectrons are focussed and swept across the CCD at a high speed. The CCD axes are aligned so that the streak tube sweep direction is parallel to the horizontal sensor axis. The horizontal resolution of the CCD therefore determines, in part, the temporal resolution of the streak camera. The vertical sensor resolution which is along the direction of the slit image will partly determine the maximum number of independent channels that the streak camera can monitor simultaneously.

Figure 2 shows the experimental results for the horizontal and vertical spatial resolutions of both the standard thick sensor and the special thinned (~ 10 μm) RCA 52501 CCD. The data were generated by imaging a standard Air Force resolution pattern using a 1.06 μm light source. The degradation of the horizontal spatial resolution at 1.06 μm wavelength for the thick CCD is due to the deep penetration of the photons into the silicon substrate. The resulting back thermo-diffusion of the electrons generated deep in the silicon to the front-side CCD wells results in the degraded horizontal resolution. A similar horizontal spatial degradation would be experienced if a thick CCD were used to image the electrons from the back side.

III. STREAK TUBE/CCD IMPLEMENTATION

Figure 3 shows a streak tube equipped with an internal CCD. The device consists of a RCA 73435 streak tube mated to a special RCA 52501 back-thinned and back e-beam illuminated CCD. The vacuum header in which the CCD is mounted is equipped with an optical window so as to enable an optical fat zero bias to be implemented from the non vacuum side. During actual CCD operation, the storage area of the sensor is blocked so that neither the LED bias light nor the electron beam illuminate that area. The streak tube has a S-1 photocathode which utilizes a modified low temperature schedule to prevent degradation of the CCD sensor. Many of the CCD parameters, such as the dark current and inter-electrode leakage, were monitored before and after photocathode processing.

In the actual operation of the streak tube/CCD device, the photocathode voltage was lowered from the usual -17 kV at the cathode down to approximately -6 kV. This reduction of the operating voltage is required to maximize the dynamic range of the total system. To illustrate this concept more clearly, let us consider two extreme cases. In the first case, if the streak camera's photocathode is at a very high negative voltage, then an incident electron onto the CCD will produce a large number of electron/hole pairs; see Eq. 1.

In the extreme case, if one incident photoelectron saturates the CCD cell, then the system dynamic range for the streak camera/CCD instrument is reduced to unity. Now consider the opposite situation; if the streak tube's photocathode is at a very low negative voltage, then an incident electron onto the sensor yields a very small number of electron/hole pairs. Again, going to the extreme, if the incident electron energy is around the dead layer value (i.e. ~ 2 keV), then the sensor gain is near unity. The dynamic range in this condition is primarily governed by the maximum photocathode current density. For an S-1 photocathode, the maximum current density is about 1000 electrons per CCD pixel per 10 picoseconds. Hence for a 10 picosecond resolution system, the number of electrons available per CCD cell is 1000. The system dynamic range in this case is less than unity since the CCD electron equivalent noise for the RCA 52501 sensor is around 10^4 electrons. Between these two extremes, the streak tube/CCD will not be limited by either photocathode saturation or by CCD well saturation, and reasonable dynamic range of several hundred can be obtained.

The streak camera/CCD data acquisition system consists of a LeCroy 8258 8-bit transient digitizer coupled to a multiplexed 192K dynamic local memory. The digitized data are processed by an LSI/11 computer through a standard CAMAC data highway. The processed data are stored on floppy disks for further analysis. A typical local LSI/11 processing consists of a point-by-point dark current subtraction followed by a CCD gain normalization. Both of the 320 x 256 point data for the dark current and sensor gain profile are stored on disk.

For most ultrafast diagnostics, system synchronization is very important. For the case of a streak camera, synchronization to the order of tens of picoseconds is generally required to prevent loss of data. This precise timing is usually provided either optically or electrically to the streak camera. For the CCD recording sensor, however, it is only necessary to time the CCD cycle such that the streak camera data are not deposited onto the sensor during the A to B transfer time, because during this time, the nonstoring CCD electrodes are brought out of accumulation and hence the sensor loses all of its anti-blooming characteristic. This rather relaxed timing requirement is implemented by phase-locking the CCD master clock to a low frequency pulse generated by the laser system's master computer. Any one of these pulses (~ 10 Hz) may be used to initiate the laser firing sequence; hence within a few microseconds after the timing pulse, the laser will generate data onto the CCD sensor. With appropriate delays, the streak camera data can always be arranged to arrive during the middle portion of the CCD integration cycle.

IV. CRT/CCD IMPLEMENTATION

Figure 4 shows a wide bandwidth CRT equipped with a CCD electron sensor. The device consists of a specially designed EG&G CRT coupled to an RCA back-thinned (~ 10 μm) 52501 CCD. The CRT deflection structure consists of a transmission line serpentine with an electrical characteristic impedance of 50 ohms. The serpentine deflection structure is designed to provide maximum signal deflection sensitivity by matching the signal phase velocity to the propagation velocity of a 5 kV electron.

The CRT/CCD is processed by baking the structure at 200°C for eight hours before cathode activation. The thermionic cathode is then aged for 24 hours to maximize and stabilize the current output. The CCD's optical imaging quality was monitored before and immediately after the processing cycle and was found to have degraded a slight amount.

The signal channel amplitude response of the CRT is shown in Fig. 5. The graph is a plot of the relative power required to deflect an electron beam vertically one centimeter at the CCD focal plain versus the frequency of the input signal. The variations of the deflection response are due to the many small local resonances of the various substructures of the deflection response are due to the many small local resonances of the various substructures of the deflection serpentine. The sensitivity of the deflection structure is measured to be approximately 10 volts per cm and the spot size at the CCD focus plane is about 200 μm. The axes of the CCD are aligned so that the signal deflection is parallel to the CCD vertical axis.

The data acquisition system required to support the CRT/CCD instrument can be identical to that described for the ultrafast streak camera/CCD system. In the CRT case, the dynamic range of the CRT/CCD is determined by the vertical spatial resolution rather than by the intensity of the electron beam. Because of this difference between the CRT and the streak camera, it is more economical to slow down the CCD scanning rate and to trade away the sensor's dynamic range, which in this case is not required, for a slower A/D and memory. In this manner it is possible to reduce the electronic system cost by a considerable amount.

In addition to the factor-of-four reduction of the CCD scanning speed, the electronics were further modified to provide a continuous scanning mode in which both the image and storage registers are clocked synchronously at all times. Both the usual image integration period and the fast A to B image transfer action of a normal T.V. mode were deleted. The remaining B to C transfer mode, in which the B shift register provides one CCD cell transfer for every 320 horizontal C shift register transfers, is extended, in the continuous mode, to include the A image registers.

By changing the clocking scheme to the continuous mode, the system can now be used only in the pulsed illumination condition. The input pulse duration must be short, compared to the CCD vertical clocking period, in order for the sensor to exhibit good vertical resolution. This pulse duration requirement is, of course, easy to satisfy for the ultrafast CRT application, since the electron beam deposits its information onto the CCD in a few nanoseconds and the vertical clocking period for the slow scan case is in the order of tens of milliseconds.

The motivation behind using this continuous scanning technique is the ease in which the CCD can be synchronized to the external world. In this mode, the CCD is always shifting out the sensor's dark current and the external A/D is continuously digitizing the output. No memory storage is implemented until after the event time, upon which the next horizontal line clocked out by the CCD is, by definition, the first line of the picture. The memory will now commence to store the first and the subsequent 255 lines at which time a complete CCD picture is then obtained.

Note that unlike the previous phase-lock technique, no prewarning synchronization pulse is required to prepare the CCD for the data-taking sequence. However, this continuous scanning mode, by its very nature, prevents the implementation of the anti-blooming technique. This lack of anti-blooming ability is not important for the CRT/CCD operation, since the beam current of the CRTs can be adjusted to prevent sensor overload.

V. CONCLUSIONS

Two ultrafast laser fusion diagnostic instruments have been designed and fabricated which incorporate a back-thinned RCA 52501 CCD sensor.

The RCA sensor has been characterized in the electron-in mode and provides relatively high gain at lower tube operating voltages. This reduced voltage can also allow effective increase deflection sensitivity in the streak tube.

In performance the 3 GHz response of the CRT was obtained.

The data acquisition system is designed to implement direct computer accessing and processing for both the CRT/CCD and streak tube/CCD instruments.

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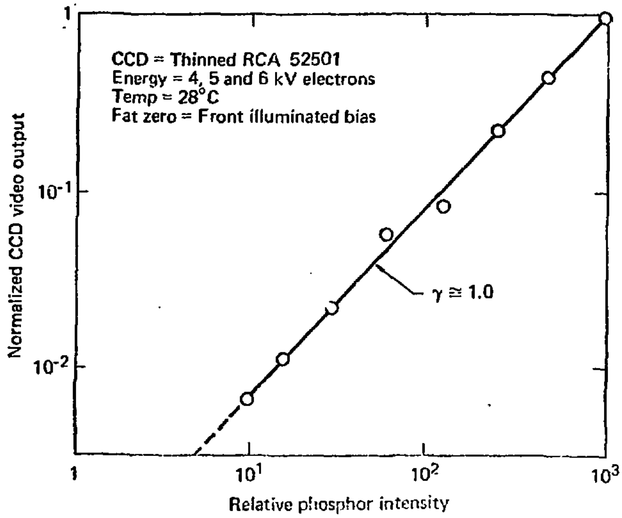

Fig. 1a. Signal Transfer Curve

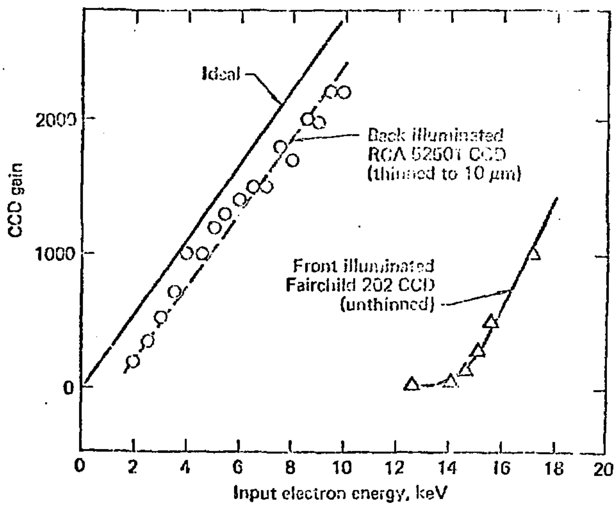

Fig. 1b. E-Beam Gain Curve

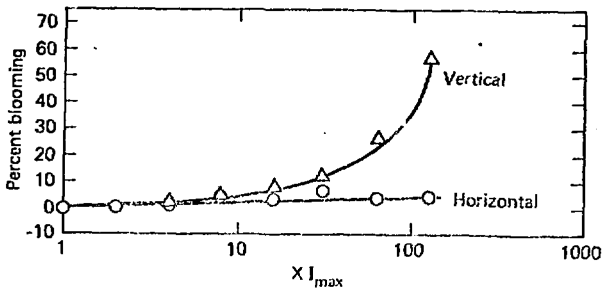

Fig. 1c. Blooming Characteristic
RCA 52501 CCD

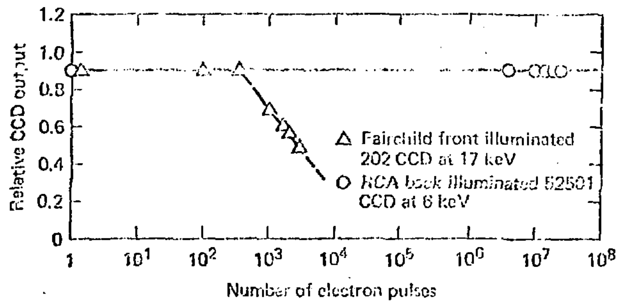

Fig. 1d. E-Beam Deterioation of CCD's

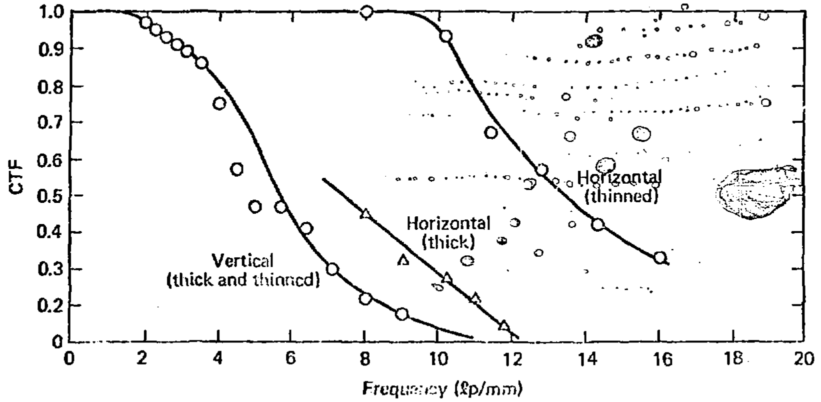

Fig. 2. Frequency Response Curve CRT/CCD

Fig. 3. Modified RCA 73435 Streak Tube
With Back-Thinned RCA 52501 CCD

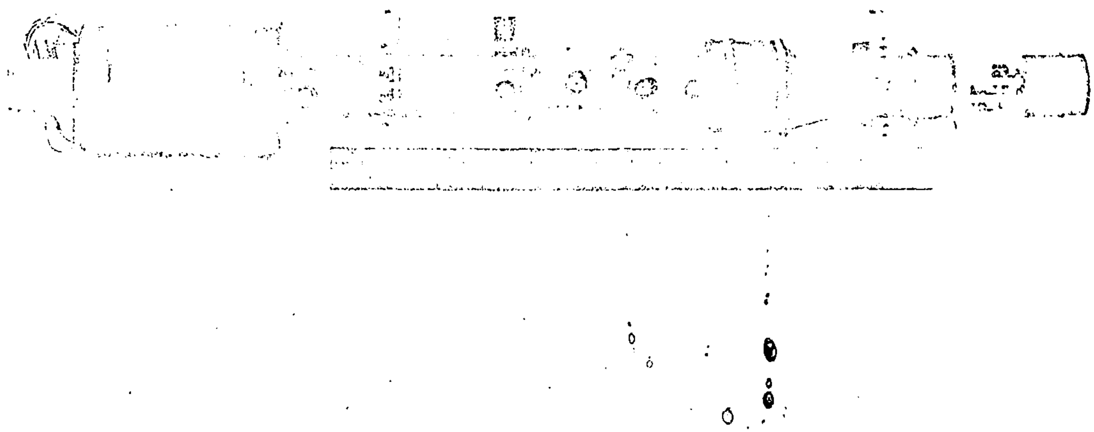

Fig. 4. Modified EG&G CRT with RCA 52501 CCD

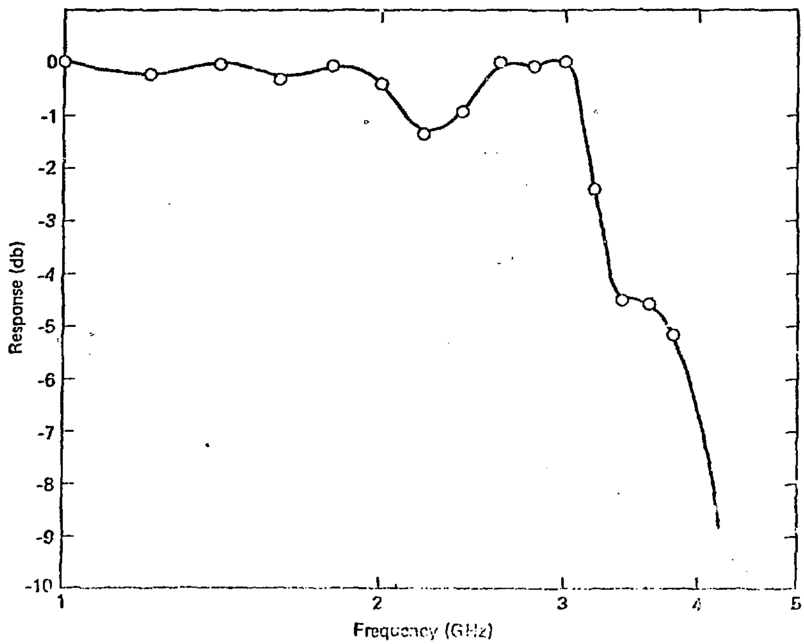

Fig. 5. Frequency Response Curve CRT/CCD

Distribution

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