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PHOTOCHROMICS IN OPTICAL SIGNAL PROCESSING,(U)

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(6) PHOTOCHROMICS IN OPTICAL SIGNAL PROCESSING,

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INTRODUCTION

Optical processing of signals has aroused considerable interest in the past several years; however, its usefulness for real-time processing of electrical signals has been limited by the lack of instantaneous recording media. Photochromic materials appear to offer a solution. Optical techniques offer three advantages:

1. Optical systems have high information capacity, e.g., storage capacity of ordinary photographic films is on the order of millions of bits per square inch. Under special conditions, much higher densities can be achieved, and similar high capacity is also obtained if media other than photographic films are used.
2. Processing of large amounts of information is done efficiently because a single process can be applied to many signals in parallel, rather than serially. The same filter function can be simultaneously applied to many signals, or a large number of filter functions can be simultaneously applied to a signal, without significant increase in system size or complexity over the one-signal, one-filter case. The correlation processors can also handle many signals and references in parallel. The combination of the high storage capacity and the parallel processing results in a highly compact system.
3. Optical processors are flexible, i.e., different filter functions may be inserted into the same space-coherent processor so that a variety of tasks may be accomplished. Or, in the incoherent processor, the reference may be changed, and many different signals can then be correlated.

If an optical processor is to replace an electronic processor, the input-output relationships of the two must be identical. This paper describes two types of optical processors, each corresponding to a broad group of electronic processors with similar input and output characteristics. Coherent devices operate on the signal to form its Fourier transform or frequency spectrum. The frequency spectrum can be operated on, and thus coherent processors are equivalent to electrical filters. In fact, any linear operation can be implemented in a coherent optical processor.

Incoherent processors form the second group to be discussed. These devices perform correlation between a pair of signals or a signal and a reference. Thus incoherent processors can be used to substitute for electronic correlators. Tests of lamps for use with photochromics in optical processors, and improvement in photochromics will be discussed. Applications to signal processing will be described, and areas for further development will be reviewed.

SLIDE 1

SPACE-COHERENT OPTICAL PROCESSOR

The basic space-coherent processor is shown. A collimated monochromatic source provides the light. The signals to be processed are placed in the front focal plane (object plane) of lens 2. Lens 2 then forms the diffraction pattern of the object in the diffraction plane. Lens 3, in turn, produces the inverse of the diffraction pattern. This inverse pattern is actually an image of the original object, and it appears in the observation plane.

Coherent processing performs, by optical means, operations equivalent to electronic filtering. The signal and operations are introduced by photographic transparencies, photochromic materials, and similar devices.

Optically, it is common to speak of the object and its diffraction pattern. For signal processing, the important fact is that the light amplitude and phase in the diffraction plane is approximately the Fourier transform of the object in the object plane.

An example will illustrate the use of the transform and its inverse. Suppose that a pulse train which is received has been contaminated with noise. As is well known, the Fourier analysis of such a square pulse train results in terms which correspond to a constant value, and to the harmonics of the pulse frequency. The electrical pulse is recorded on film as alternating opaque and transparent bars. The Fourier transform of the pulse may be viewed in the diffraction plane; the spots of light correspond to the constant value, and to the first, second, third, etc., harmonics of the fundamental frequency of the pulse.

If the pulse is contaminated with noise, the Fourier transform will be altered. Now, if a mask is made to correspond exactly to the diffraction pattern of the pulse train, it can be inserted in the diffraction plane so that only those frequency components of the contaminated signal that correspond to the original signal will pass through. Frequency components corresponding to noise will be blocked out. Thus the signal, free of noise, will be seen in the observation plane.

SLIDE 2

OPTICAL CORRELATOR

The optical correlator is used to determine the time delay between signals received at two receivers, or to identify a significant waveform in the presence of other waveforms. Two signals, printed on separate films or plates intercept a collimated beam. The slide shows a configuration for the identification of a particular waveform: S2 is stationary (the waveform of interest) while S1 is moving. The collecting lens and photomultiplier serve to multiply and integrate the two signals as shown in the equation. If S_1 and S_2 are identical, A(t) is the autocorrelation function of the inputs. For example, if S_1 and S_2 are random noise functions, A(t) will have a narrow peak when the delay between S_1 and S_2 is zero.

SLIDE 3

PHOTOCHROMIC MEASUREMENT APPARATUS

Studies were initiated to determine the best means for utilizing photochromic material in an optical processor. The first step was to measure the writing, reading, and erasing parameters of the films available. A block diagram is shown of the test apparatus.

The write monochromator is a Perkin-Elmer Model 99 double-pass prism monochromator with a 60^{o} fused quartz prism. Only the single-pass dispersed output of the monochromator was used. The spectral width of the monochromatic light output was 40Å in the ultraviolet and 80Å in the visible. The output was focussed on the photochromic sample by a quartz lens to form a circular spot about 3/32 inch in diameter.

At the output of the monochromator was a custom made, high-precision, electro-mechanical shutter. The shutter consisted of a spring-driven conventional shutter for rough exposure control. In tandem with it was a slit wheel driven by a synchronous motor through a variable-ratio gear drive. The resulting shutter provided precise exposure times from milliseconds to 6 seconds.

The output of the write monochromator was measured at least once each day. The exposed material then is rotated so that it passes in front of the "read monochromator". The samples were square 8 to 9-1/2 inches on a side. They were mounted on an axle so that they could be rotated either manually or at the fixed speed of 24 r.p.m. by a synchronous motor through a gear drive.

The read monochromator is a Perkin-Elmer Model 98-G diffraction grating monochromator. The light out of the monochromator is imaged by a lens onto the photochromic surface to form a spot. This spot is 0.012 inches in diameter located in the center of the 3/32 inch width of the 7 inch diameter track written by the write monochromator. The spot size limits the minimum detectable variations in the photochromic material also to about 0.012 inches in size.

The portion of the read-monochromator light which is transmitted by the photochromic sample hits a front-surface mirror, goes through a lens onto an RCA 1P21 photomultiplier. Thus the voltage out of the photomultiplier is proportional to the transmission of the photochromic sample. The photomultiplier lens reimages the output aperture of the read monochromator onto the photomultiplier. This way small vibrations of the photochromic sample have little effect on output voltage. Using a .012 inch scanning light spot over the 7 inch radius and the rotational rate of 24 R.P.M. infer that the upper frequency of the output is about 4 KC. The photomultiplier is followed by a two-stage R-C low-pass filter with the cutoff frequency of 10 KC.

In general, manufacturers claims of the sensitivity of their photochromics were found to be accurate.

SLIDE 4

WRITE LAMP TEST

The next test undertaken was to determine the rate at which information can be printed on photochromic material. A block diagram of the test setup is shown. A modulating lamp driver was designed and built. This modulator drove a mercury arc lamp in the pulse-simmer mode. The lamp operates at rated (or higher) current when the modulating signal is negative, and at the minimum current required to maintain the arc when the modulating signal is positive. Since the light output drops sharply when the lamp is operated below rated current, the lamp writes a series of marks and spaces on the photochromic material.

The mercury arc light passed through a beam splitter, into the microscope objective, and onto the rotating photochromic plate. (The photomultiplier was shielded during writing.) Light reflected by the photochromic plate was returned through the beamsplitter to the microscope objective, thus providing an easy method of focusing. A yellow filter allowed alignment and focusing without writing on the plate.

The mercury lamp light was then allowed to fall on the photochromic plate for a period of one revolution, producing a band of information. The mercury lamp illumination was blocked off and the beamsplitter reversed, to permit the dc lamp illumination to fall on the photochromic. The dc lamp was positioned so as to form a spot on the photochromic superimposed on the band written by the mercury arc lamp. The photomultiplier was used to observe the modulation of the dc light caused by the spot pattern on the photochromic. Successful recording, storage, and readout were obtained at rates up to the high audio range. The switching characteristics of the modulating transistor were at least a contributing cause to preventing higher frequency operation.

SLIDE 5

PHOTOCHROMIC MATERIAL CHARACTERISTICS

The photochromic material selected for use in the optical processor is type 43-540 manufactured by American Cyanamid Company. This material was chosen as being most sensitive to the ultraviolet writing light. An additional advantage, as compared to some alternates, is that the absorption in the colored state is in the green portion of the spectrum, a region well removed from the writing spectrum, so that there is no writing caused by the reading illumination.

In order to take full advantage of the high concentration of ultraviolet light provided by the condenser lens, it was necessary to obtain a thin, flat coating of photochromic material on a rigid substrate. The most common formulations of photochromic material had been either as films of 3 to 5-mil thickness, or as acrylic sheets with the photochromic material distributed through the 1/16- to 1/4-inch thick plastic.

To provide the configuration required, it was decided to use 1/4-inch thick microflat plate glass as a substrate, and to coat the glass with a thin layer of photochromic material. Gravity flow coating was tried but wedging occurred because the photochromic material dried as it flowed down the plate. Spin coating was then used, with much better results. The ultimate configuration was a photochromic layer approximately 10 microns thick on a 1/4-inch selected flat plate. Tests had shown that the microflat quality (0.00002 inch/linear inch) was not necessary; selected flat (0.001 inch/linear inch) was sufficient.

Noise inherent in the prepared plates was reduced by taking precautions to prevent dust particles from falling on or being attracted to the photochromic surface during the drying period, and to prevent scratches and other surface blemishes from occurring during handling prior to use. Since the coating is quite soft even after drying, this requires careful handling.

SLIDE 6

ERASE LAMPS

Although far from ideal spectrally, xenon flash tubes and compact arc lamps were tested first. The plastic base in which the photochromic dye is dissolved absorbs infrared radiation; it was thought that the resulting heat would help in erasure. The flash tubes showed some erasing capability, but were quickly eliminated because of the inconvenience of pulsed operation in a continuous system.

A deep half-ellipsoid was fabricated to concentrate the compact arc's radiation onto the photochromic plate. Good focusing was obtained. However, as an erase lamp the xenon arc was not effective; when well focussed, the infrared energy burned the plastic film, and when defocussed to prevent burning, the erasing was poor.

Further examination of the test results showed that erasing was being accomplished by the heating of the plate. With an unfiltered xenon arc in the ellipsoidal reflector, three regions could be distinguished. At the focus, the film discolored due to overheating. Near the focus, erasing took place, while further from the focus writing was observed. Since the spectrum of the radiation will not vary in space in a reflecting system, the cause of the differences must have been the different temperatures caused by the decrease in irradiance as a function of distance from the focus. Where the temperature was higher, the bleaching reaction predominates; where the temperature remains low, the writing reaction is stronger.

Attempts to use filters with the xenon lamp to absorb the ultraviolet radiation were unsuccessful. The sharp-cut yellow filters absorb a good deal of near infrared radiation. This prevented the temperature at the photochromic from reaching the level required for erasing. Also, the filters cracked from overheating unless cooled. The need for a better erase lamp was evident.

Both the Lucalox (General Electric) and CSI (Phillips) are relatively new and became available during 1965. As is evident from their spectra they are much better suited to erasing photochromic than the xenon lamp. Not only is their more radiation in the 530 to 610 mu band, but very little in the infrared, so that burning of the photochromic and cracking of filters is less of a problem.

Both lamps were tested, a 400-Watt Lucalox and a 250-Watt CSI. Elliptical cylinder reflectors and sharp-cut yellow filters were used. Taking account of the differing power levels, the erasing effectiveness was about equal. The CSI was chosen because its luminous tube length is about 1" as compared to 4" for the Lucalox. The shorter arc makes for a more compact lamp housing.

SLIDE 7

COHERENT PROCESSOR TEST

A laboratory test program was conducted to see how well photochromics can be applied to coherent processing. The major area of concern was that the non-uniformities in the photochromic coating may show up as noise in the output plane. Hence the major purpose of the program was to measure output signal-to-noise ratios. As a test pattern, Ronchi rulings were used. The Ronchi rulings were contact printed onto the photochromic material, which were then placed into a coherent processor. The resulting output was scanned by a microscope-photomultiplier combination and recorded by an X-Y recorder. From the recordings, the signal-to-noise ratios were computed.

The test setup is shown. It consists, first, of the collimator to supply the coherent light. The collimator is followed by a 1000 cps chopper which, in conjunction with the 1000 cps band-pass filter at the output of the photomultiplier, discriminates against prevalent low (temporal) frequency noises. After the chopper, the photochromic input transparency is inserted, to be followed by the Fourier transforming lens. The DC Fourier transform (zero-order diffraction pattern) is blocked out at the Fourier transform plane to avoid damaging the photomultiplier. The rest of the light pattern representing the Fourier transform is scanned by a moving microscope-photomultiplier combination. The filtered output of the photomultiplier was applied to one axis of an X-Y recorder. The other axis was controlled by a potentiometer so that it indicated the position of the scanner. The result was a direct plot of light intensity versus position in the Fourier plane, or the actual, optically-derived Fourier power spectrum.

Photochromic film offers an advantage over photographic film: in photographic film, the unexposed emulsion is washed away during development, leaving a transparency of uneven thickness, resulting in phase distortions in the coherent light. Phase compensation must be used to obtain correct outputs. These compensation methods are not needed with photochromics, since the photochromic material does not change thickness as a function of exposure.

SLIDE 8

PHOTOCHROMIC OPTICAL CORRELATOR - BLOCK DIAGRAM

Slide 8 is a block diagram of a correlator built for the Navy*. The following functions are performed:

- Two signals, A and B, are recorded as a bands of marks and spaces on two rotating photochromic plates.
- The B plate is stopped. The A plate continues to rotate. Light from an illuminator passes through the B signal band, the semicircular slit, and the A signal band, and is detected by a photomultiplier. The photomultiplier output is the correlogram of the two signals. A microswitch actuated by Plate A allows the correlogram features to be interpreted in terms of time delay between the two signals.
- After the correlogram has been observed, the erase lamps are ignited, and the signals are removed from the plates. The sequence can now be repeated.

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* U.S. Navy, Ship Systems Command, Contract NObsr 93299

SLIDE 9

PHOTOCHROMIC OPTICAL CORRELATOR

A photograph of the correlator is shown. The elements corresponding to the block diagram are identified.

SLIDE 10

CORRELATOR TEST

A complete circle of signal was written. A portion of the circle was printed at the test frequency, F1, while other portions were printed at higher and lower frequencies F2 and F3. The test frequency was printed on the stationary photochromic plate. Results are shown. The photo shows three successive traces. The writing on the moving disk was

Box	Frequency (cps)
0-10	F1
10-18	F2
18-25	F1
25-28	F3
28-	F1

The sine wave correlogram is seen as expected. In addition, beat frequencies are seen during the F2 and F3 intervals.

SLIDE 11

PHOTOCHROMIC EXPONENTIAL INTEGRATOR

The input signal function A_n modulates the mercury arc light source with the aid of an amplifier and lamp driver. The photochromic disk rotates, and the signal may be read out by read lamp R and photomultiplier P. The erase lamp E reduces the level of the recorded signal by a factor, such that the remaining signal is $(KA_1)'$. The second signal segment is written superimposed on the first signal. If the sum is now read out, the total is

$$KA_1 + A_2$$

and after n iterations of the process

$$K^{n-1}A_1 + K^{n-2}A_2 + ----+ KA_{n-1} + A_n$$

Thus exponential summing of signal functions is accomplished with a minimum of electronics.

Eventually the erase lamp will reduce A_1 to below the noise level of the photochromic and A_1 will be eliminated from the integration. By adjusting the erase rate, the factor K can be varied. In this scheme the integrator can be used continuously over relatively long periods.

The advantages are as follows:

a) In an optical correlator using photochromic material, this integrator is more easily implemented than an electronic integrator.

b) The optical integrator can integrate longer period signal segments than electronic integrators commonly used for this purpose.

c) The optical integrator has the possibility of being more compact and less expensive than the electronic integrators of comparable or lesser performance.

SLIDE 12

ULTRAVIOLET LASERS

The principal candidates for the most efficient ultraviolet laser are the following:

a. Krypton - There is a strong line at 3507Å in doubly ionized krypton (Kr III) which has produced the highest published output power in this range, 300 mw. This fact alone makes this line worthy of study, even though it was achieved in a tube which showed bore erosion and gas evolution at the required current densities.

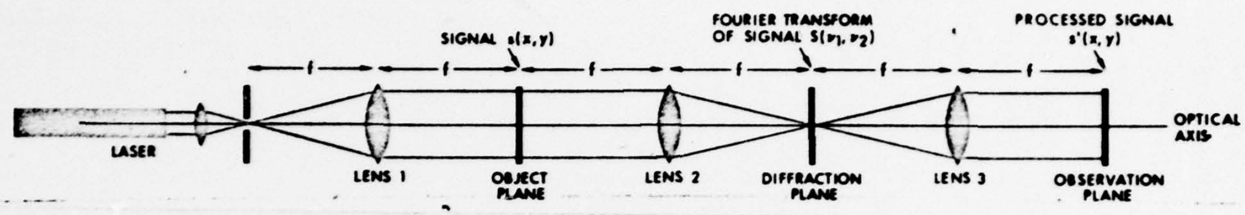
b. Argon - There are two strong lines in Ar III at 3511Å and 3638Å. These lines do not share common levels and, hence, oscillate independently. For those applications which can use both wavelengths simultaneously, such as writing on photochromic materials, this simultaneous operation offers the prospect of doubling the useful output power.

c. Neon - There is a strong line in singly ionized neon (Ne II) at 3713Å. This line is the analog of the 4880Å line in Ar II which is the most efficient ion laser line. In addition, Ne II has a cluster of three strong lines at 3324Å, 3378Å, and 3393Å. However, the 3324Å and 3393Å lines share a common upper level and the 3378Å and 3393Å lines share a common lower level, which means that very little can be gained from simultaneous operation and competition effects may be harmful. Nevertheless, the 3324Å line has the lowest published threshold.

CONCLUSION

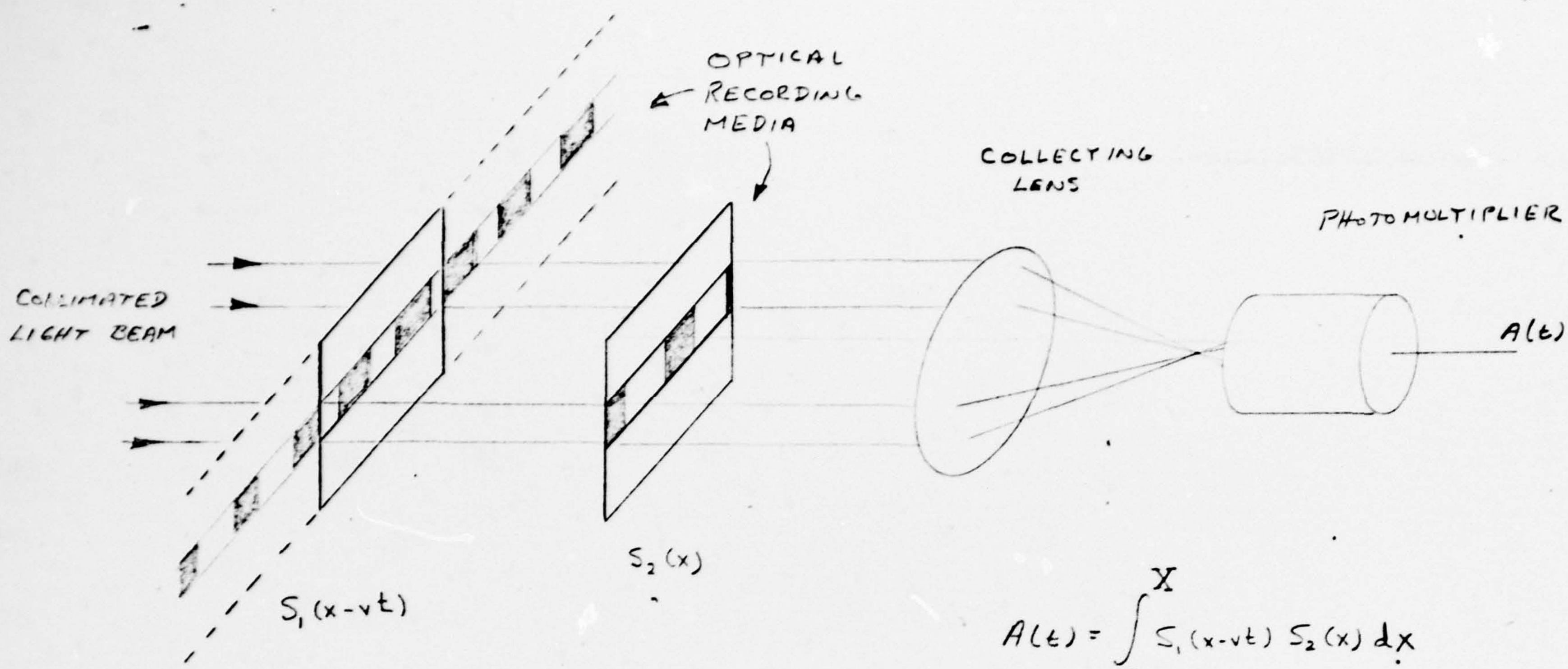
Our work shows that photochromic material can be used successfully in optical signal processors. Ultraviolet lasers will provide higher energy densities at the photochromic surface. These energy densities are obtained without the necessity for high numerical aperture optical elements, thus permitting greater design flexibility. These lasers, combined with further work in improved photochromics, will widen the area of useful applications.

SLIDE 1



SPACE- COHERENT OPTICAL PROCESSOR

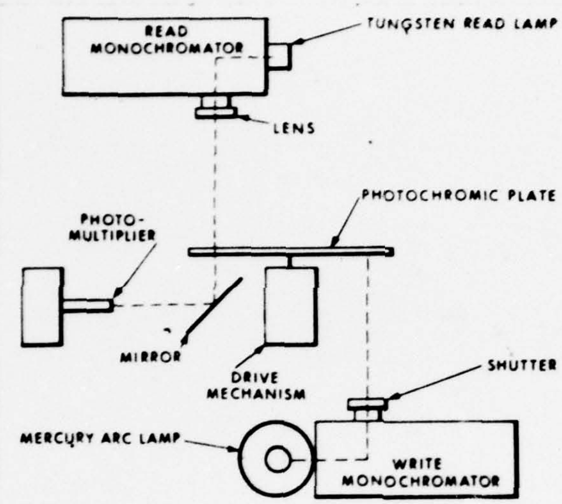
SLIDE 2



$$A(t) = \int_{-X}^{X} S_1(x-vt)\, S_2(x)\, dx$$

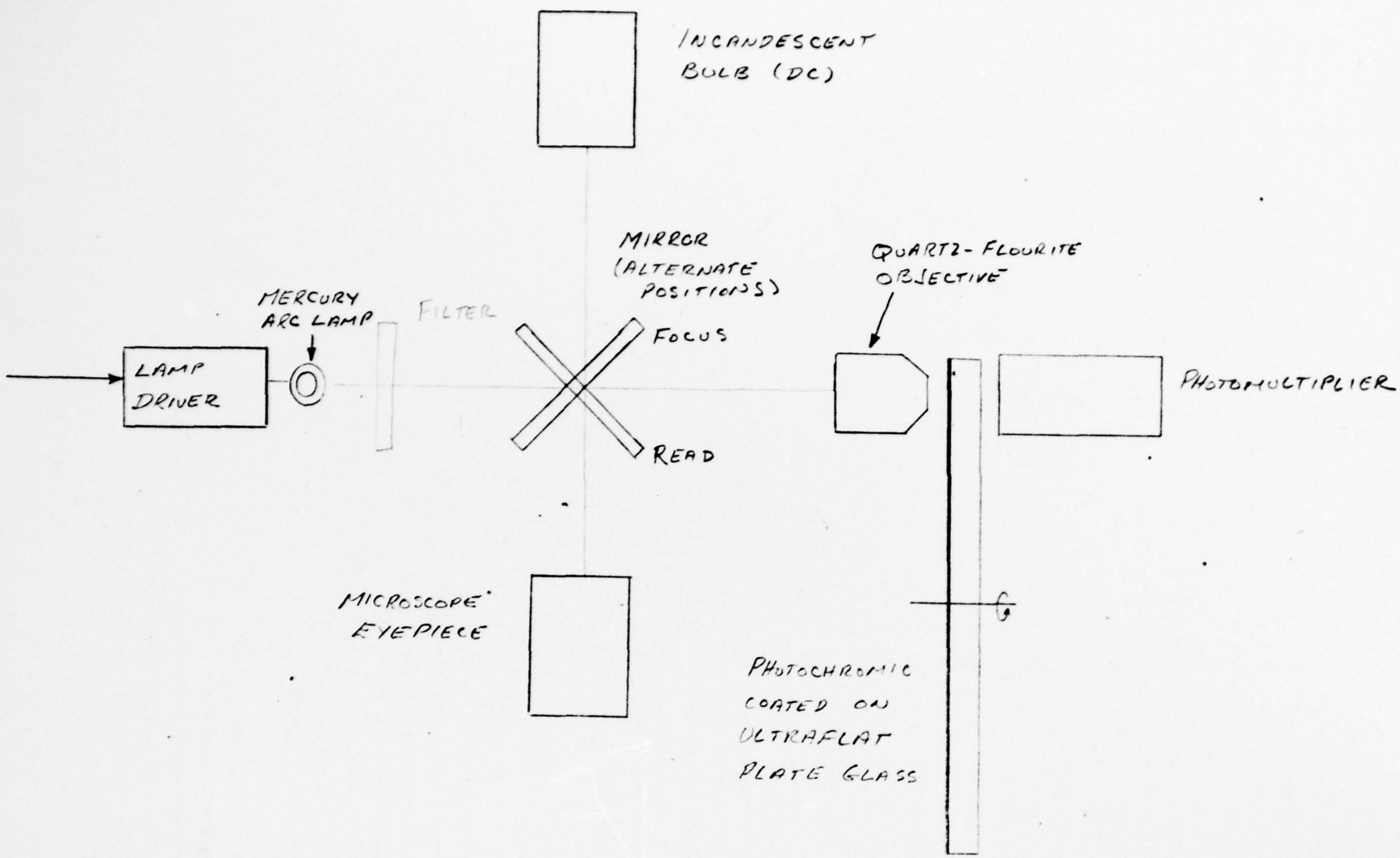
OPTICAL CORRELATOR

SLIDE 3



PHOTOCHROMIC MEASUREMENT APPARATUS

SLIDE 4



WRITE LAMP TEST

SLIDE 5

American Cyanamid Type 43-540

7 percent concentration, 10% solids

Spin coated on 1/4 inch thick ultraflat plate glass

Coating thickness: 4×10^{-4} inch

Flatness: 5×10^{-4} inch/linear inch

Dust-and scratch-free

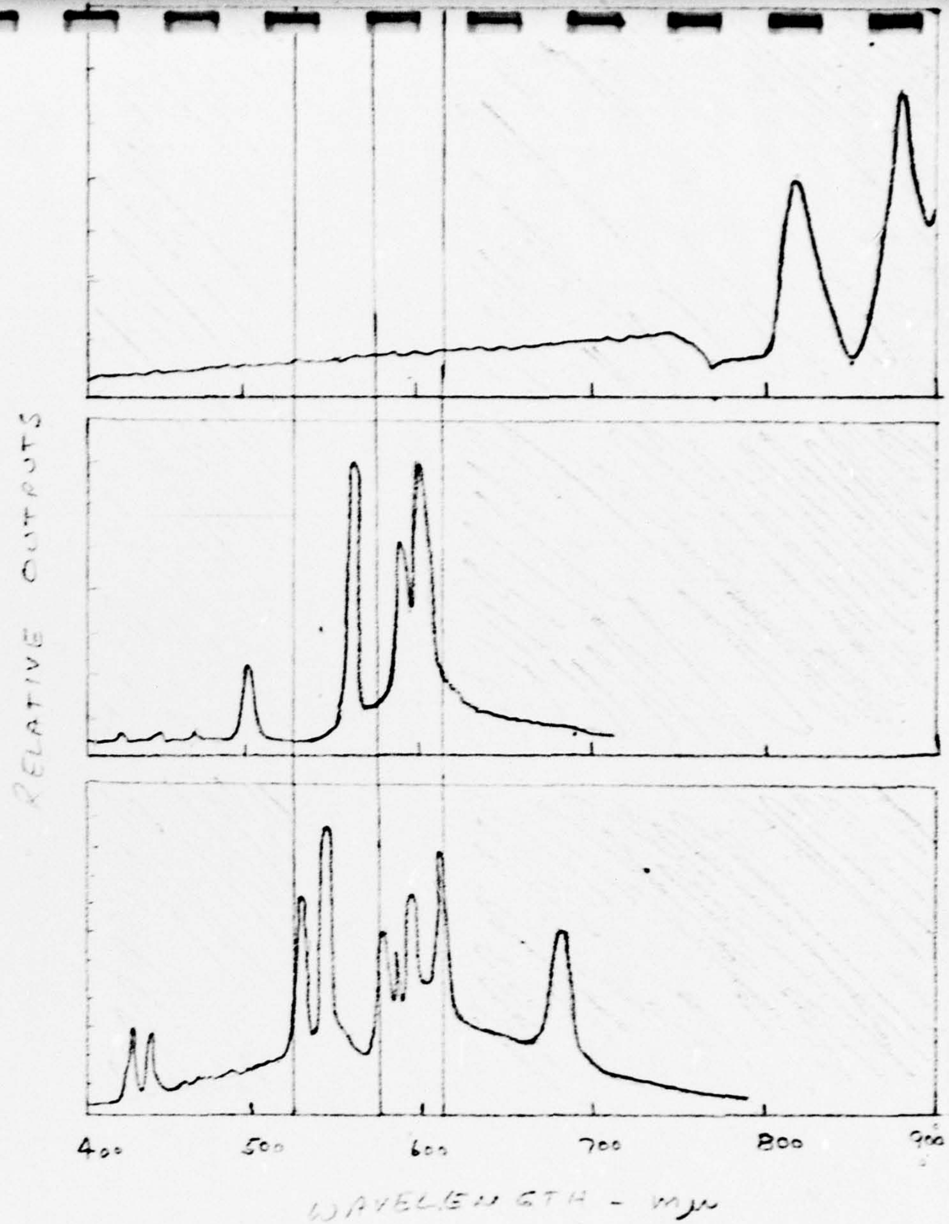
PHOTOCHROMIC MATERIAL CHARACTERISTICS

SLIDE 6

XENON – MOST COMPACT
– IR RADIATION

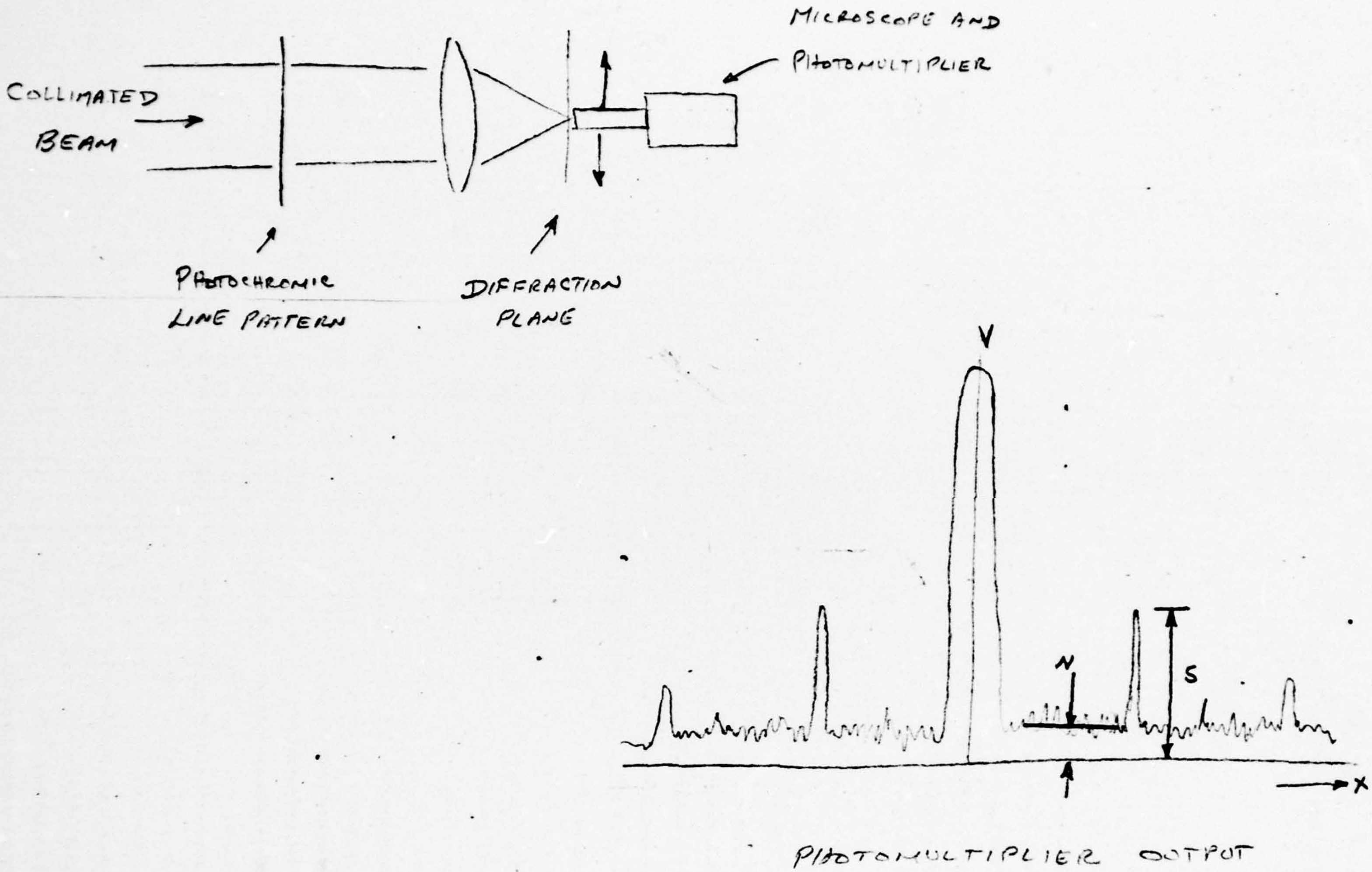
LUCALOX – 3-INCH TUBE
– 400 WATTS

CSI – 1-INCH TUBE
– 250 WATTS



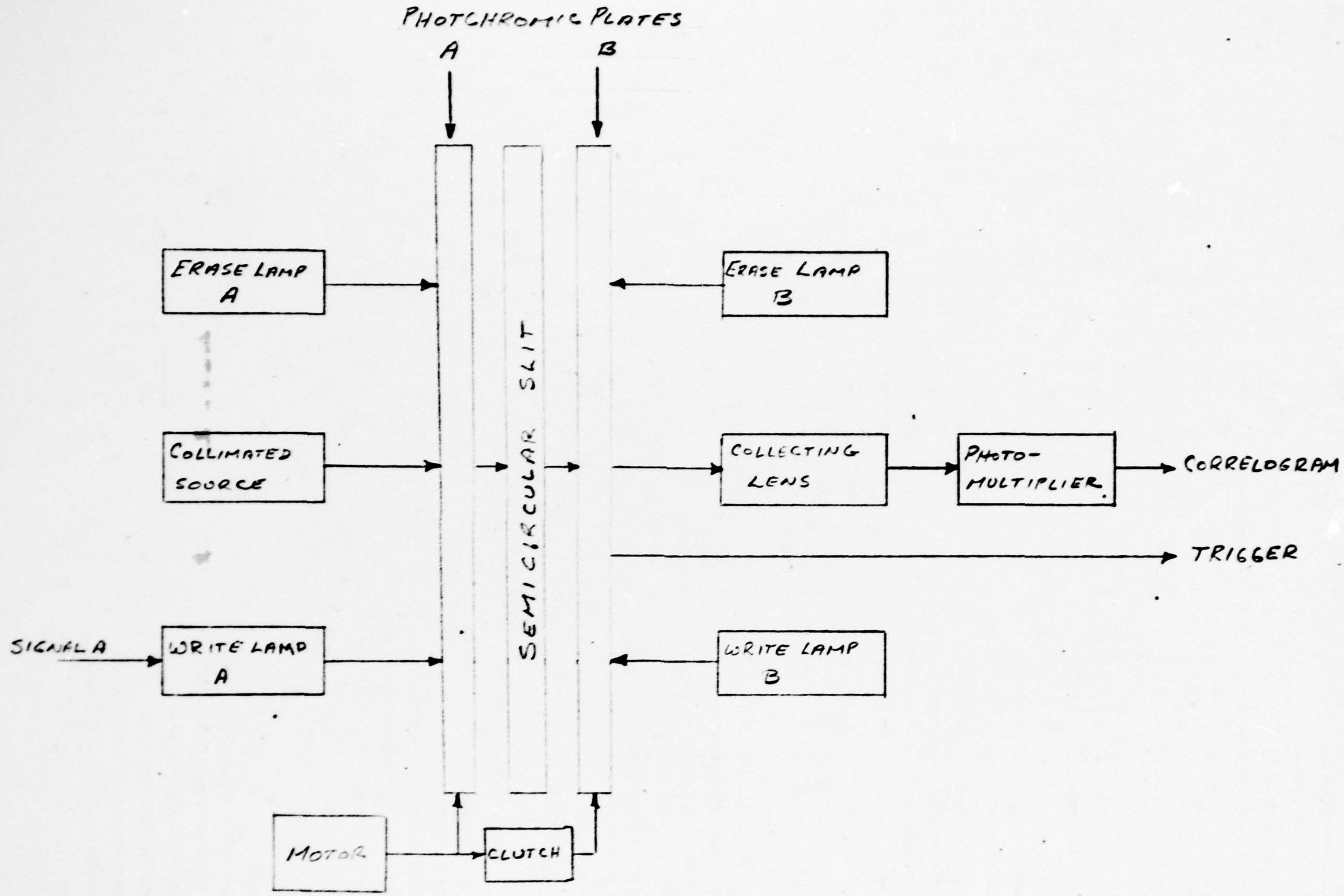
ERASE LAMPS

SLIDE 7



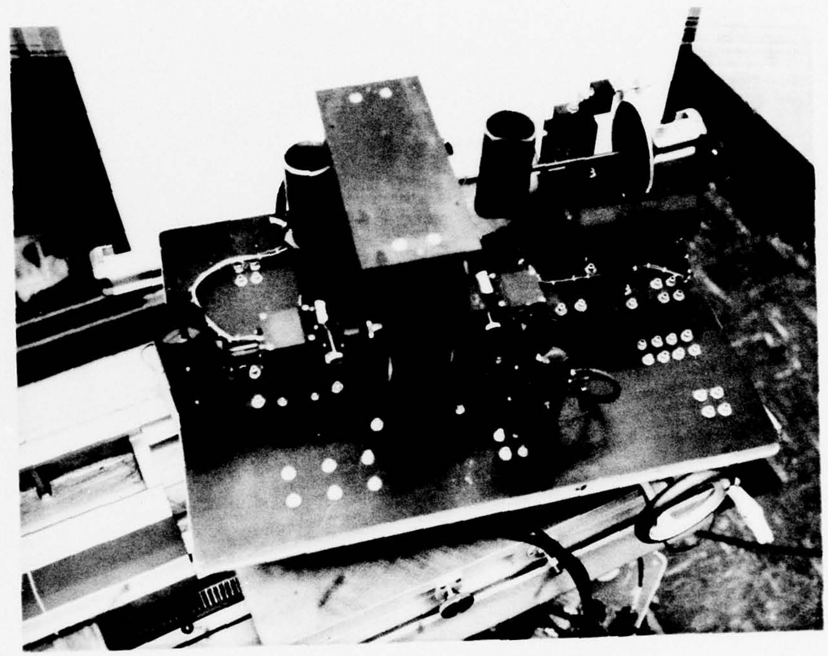
COHERENT PROCESSOR TEST

SLIDE 8



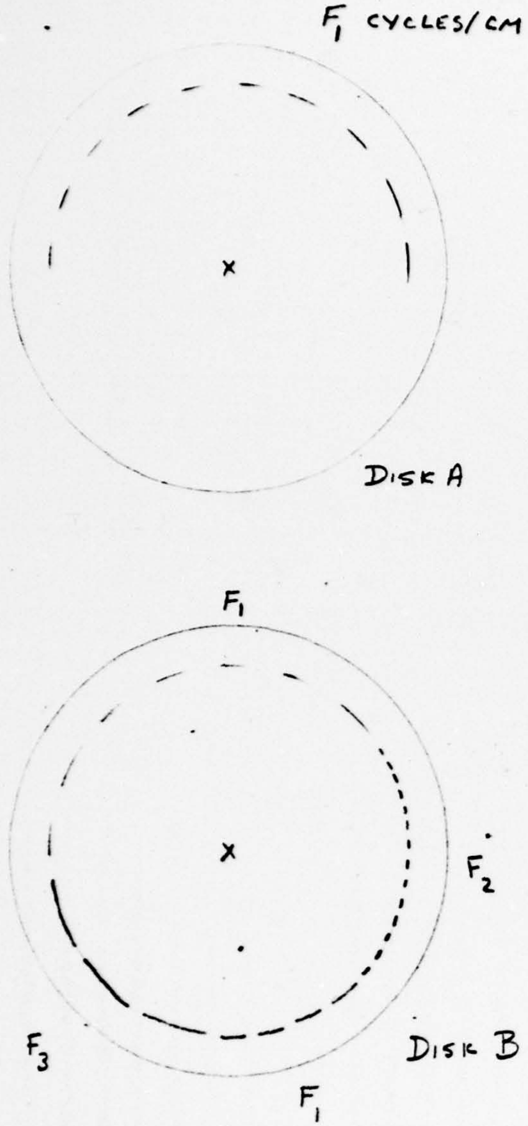
PHOTOCHROMIC OPTICAL CORRELATOR - BLOCK DIAGRAM

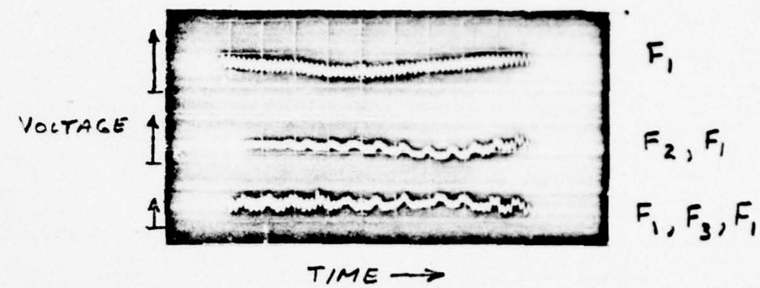
SLIDE 9



PHOTOCHROMIC OPTICAL CORRELATOR

SLIDE 10

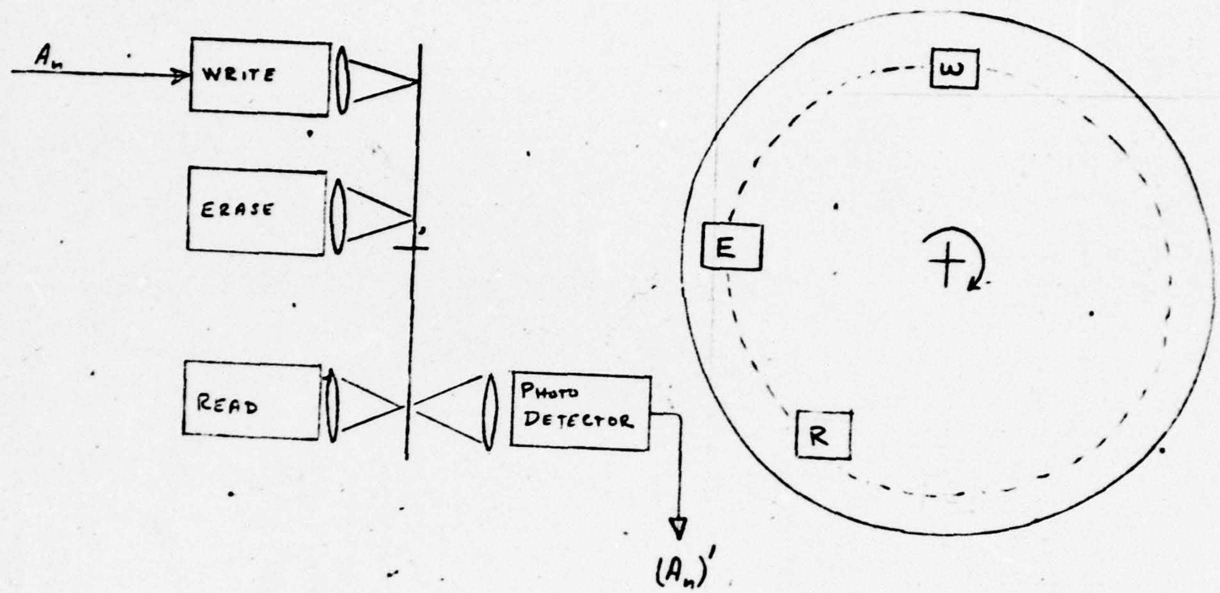




PHOTOMULTIPLIER OUTPUT

CORRELATOR TEST

SLIDE 11



$$(A_n)' = K^{n-1}A_1 + K^{n-2}A_2 + \cdots + KA_{n-1} + A_n$$

PHOTOCHROMIC EXPONENTIAL INTEGRATOR

SLIDE 12

SLIDE 11

Gas	Wavelength (Å)	Power (mW)	Current (A)
Ne^{+}	3324	30	—
	3378	10	13
	3393	—	—
	3713	—	—
Ar^{++}	3511	13	72
	3638	20	40
Kr^{++}	3507	300	72

ULTRAVIOLET LASERS