LINEAR CHARGE COUPLED DEVICE DETECTOR ARRAY FOR IMAGING LIGHT PROPAGATING IN AN INTEGRATED THIN-FILM OPTICAL WAVEGUIDE*

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ABSTRACT

We will discuss device design, fabrication, and operation of a linear charge coupled device (CCD) detector array integrated with a thin-film optical waveguide and applications of this structure to integrated optical signal processing and fiber optical communications. A two-phase, overlapping-gate CCD is connected in parallel by means of a series of gates to an array of photodiodes. The photodiode provides an electrode-free surface region so that a highly-efficient waveguide-detector coupling technique can be implemented. A thermally-oxidized layer of SiO_2 forms an effective substrate for the optical waveguide.

I. INTRODUCTION

A CCD linear imaging array integrated with an optical waveguide structure has been fabricated and successfully operated. In this integrated device guided optical waves propagate along the wafer surface entering the imaging device laterally as opposed to from the top or bottom of the device as in conventional imaging devices. Light can be confined in a thin-film in the transverse dimension perpendicular to the film surface by having a film thickness on the order of the optical wavelength and a refractive index greater than that of the substrate. As a thick layer of SiO_2 having refractive index n = 1.46 serves as the effective substrate for the thin-film waveguide, a wide variety of thin films having a larger refractive index can be utilized to form optical waveguides. If the film is uniform along the direction parallel to the axis of the detector array, a slab waveguide exists and the function of the CCD linear detector array is to image light in this transverse direction. This light variation could be the result of parallel optical signal processing performed at another location in the optical waveguide. Alternately, a number of parallel channel waveguides could be defined photolithographically with each channel waveguide coupling to a single array element. Although both types of structures are expected to find applications in signal processing and optical communications, the present discussion will generally be confined to the slab waveguide structure.

II. DEVICE STRUCTURE AND OPERATION

The integrated optical waveguide and CCD linear image array are formed on a common silicon substrate with the optical waveguide being formed on a layer of SiO_2. This layer is sufficiently thick (typically $\gtrsim$ 1 μm.) so that evanescent coupling of light from the waveguide to silicon is negligible, except in the detector region. In the detector region, the SiO_2 layer tapers to zero thickness so that light in the waveguide is coupled into the silicon substrate.[1] A taper which minimizes optical scatter is formed by allowing a carefully controlled amount of undercutting to occur during etching in device processing. A profile of the integrated waveguide - CCD detector structure is shown in Figure 1. Note in Figure 1 that the waveguide is continuous along the diode region instead of directed and terminated onto this region. Such a configuration causes the light reflected from the waveguide-silicon interface to be totally-internally reflected from the waveguide surface and incident again on the waveguide-silicon interface. Since the waveguide continues along the detector region, this process repeats itself many times. The resulting multiple refraction of light into the detector minimizes detector loss due to reflection.

The detector array in Figure 1 consists of an array of photodiodes formed in n-type silicon connected in parallel by means of a series of gates to a CCD shift register. The charge transfer portion of the device utilizes a two-phase, overlapping-gate structure consisting of one level of polysilicon electrodes insulated by an additional layer of SiO_2 from a second level of overlapping aluminum electrodes.[2] One CCD unit cell corresponds to each photodiode. Channel isolation is maintained through the series of gates by the presence of channel stopping n+ regions. The detector array integrates the optical signal incident on the array of photodiodes as the potentials of the control and integration gates are adjusted so that charge excited by incident light collects underneath the integration gate. At the end of the integration period T, the transfer gate is turned on so that the collected charge is transferred into the shift register. This charge transfer occurs simultaneously for each array element and in a time less than 1/2 of the CCD clock period. Once this charge has transferred into the shift register, the transfer gate is turned off and the charge is shifted along the register to the end where a serial, discrete-time signal emerges representing the spatial light distribution. As soon as the transfer gate is turned off, the photosensors begin integrating

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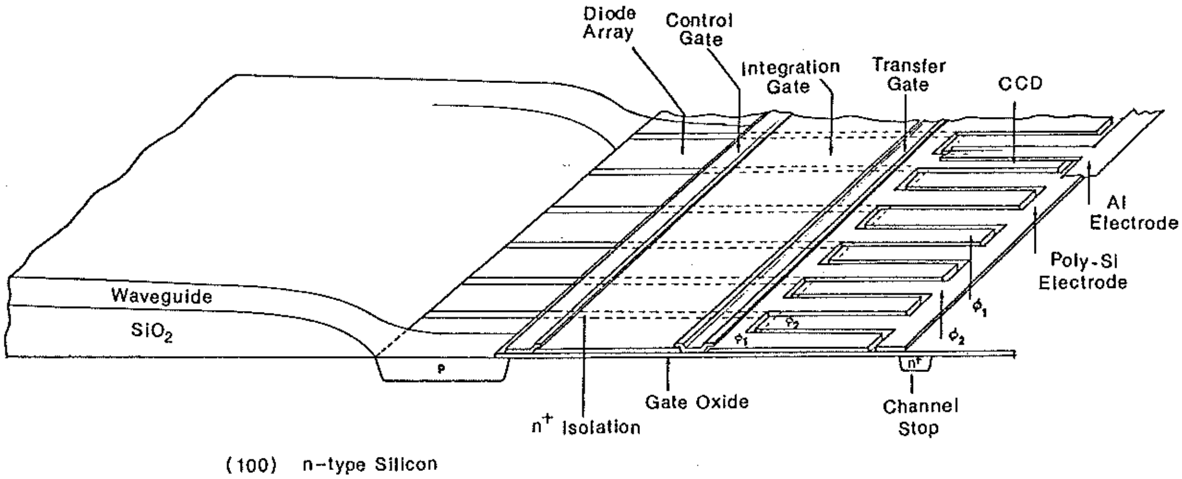

Figure 1. Integrated optical waveguide and CCD detector array.

charge and the cycle is repeated. The integration time is thus N times the lock period where N is the number of CCD cells equal to the number of array elements. Because charge integration can occur while CCD readout takes place, sensing takes place essentially 100% of the time.[3] For many applications of the integrated waveguide - CCD detector array, minimizing the array element center-to-center spacing allows the information handling capability to be maximized.[4] Such spacings will generally be limited by lithography considerations. Large aspects ratios of the rectangular photodiode region are generally undesirable. The question thus arises as to whether the extent of the photodiode in the direction of light propagation L can be chosen sufficiently large so that nearly all light incident can be multiply refracted into the detector region. To examine this question, we consider the decay of light intensity along the photodiode surface in the direction of light propagation I(z), given as

$$I(z) = I_0 e^{-\alpha_e z} \qquad (1)$$

In (1) α_e is an effective decay constant accounting for light coupled into the photodiode region given as

$$\alpha_e = \frac{1-R}{d \tan \theta}, \qquad (2)$$

where d is the waveguide thickness and θ is the waveguide mode characteristic angle with respect the waveguide surface normal. R in (2) is the appropriate Fresnel reflection coefficient at the waveguide-silicon interface for the mode characteristic angle and polarization in question.[6] We will restrict our present discussion to the TE_0 mode. For a thin SiO_2 layer in the photodiode region evanescent wave coupling will occur causing the field in the waveguide to decay according to (1) and (2), but with R interpreted more generally as a composite reflection coefficient. As evanescent coupling is weaker than multiple refractive coupling, multiple refraction is preferred as it allows minimization of the photodiode length L required for efficient coupling. An analysis of photodiode quantum efficiency for the type of waveguide coupling described herein has shown that for a variety of situations the quantum efficiency increases with $\alpha_e L$ until $\alpha_e L \sim 3$.[1] Since further increase of $\alpha_e L$ causes no significant increase in quantum efficiency, an optimum value of detector length L_0 can be defined as

$$L_0 = 3/\alpha_e. \qquad (3)$$

The magnitude of the device quantum efficiency for detector lengths greater than (3) saturates at a value determined by the silicon absorption coefficient at the wavelength of interest, depletion region depth, carrier diffusion lengths, and depth of the surface recombination region.

We have calculated the optimum detector length L_0 for the TE_0 mode as a function of waveguide thickness d for a waveguide refractive index of $n_g = 1.61$. This refractive index is characteristic of the KPR photoresist waveguides used in the experiments described herein, as well as characteristic of 7059 sputtered glass waveguides. The result of the calculation is shown in Figure 2 for $\lambda = .9$ μm and .6 μm. The portions of the curves to the left of the dotted vertical lines are the regions in which only a single TE mode can exist. In the single mode regions the optimum detector lengths would allow fabrication of efficient photodiodes with reasonable aspect ratios and with center-to-center spacings approaching photolithographic limits. However, for multimode waveguides the corresponding optimum detector lengths become quite long. It is fortunate that in many signal processing applications use of a single-mode waveguide is advantageous in view of other considerations.[4] In Fourier optical processing utilizing optical waveguide lenses the integrated waveguide-detector array described herein would find application in focal imaging. If L_0 exceeds

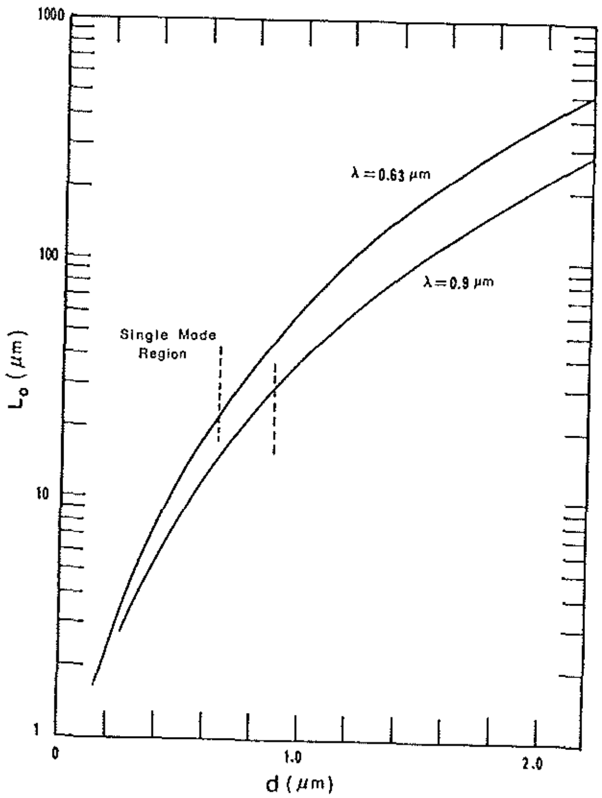

Figure 2. Detector length for efficient coupling of light from waveguide to detector as a function of waveguide thickness for a waveguide refractive index n = 1.61.

the depth of focus for such applications, then an array of channel waveguides, one passing directly over each photodiode would be required to preserve signal integrity.

The integrated waveguide-CCD detector array configuation shown in Figure 1 was fabricated using n type silicon having resistivity of 8 ohm-cm. and 100 orientation. The detector portion of the resulting device is shown in Figure 3. This device contains 19 array elements with the photodiodes measuring 25 μm x 115 μm with 7 μm of isolation between adjacent elements. In view of Figure 2, the photodiode length of 115 μm is quite sufficient for effective coupling for the KPR photoresist waveguide employed in our experiments. However, this length would be somewhat long if we were to attempt to reduce the center-to-center spacing to the photolithographic limit. The two-phase overlapping gate CCD has a conventional charge collection diode for signal output and a charge injection diode for serial input. The latter allows for electronic evaluation of the CCD and for serial injection of bias charge.

After initial probe testing of fabricated devices, individual arrays were mounted and bonded in dual-in-line packages. The packages employed were specifically altered so they could accomodate a sufficiently large piece of silicon that would allow space for prism coupling of light into the waveguide and for waveguide propagation. Once packaged the devices could then be inserted in a

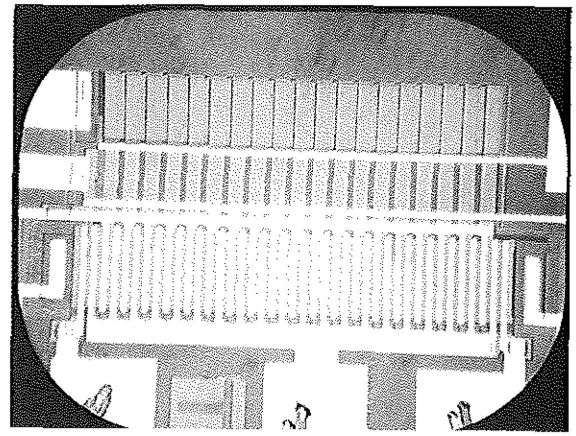

Figure 3. Linear photodiode imaging array coupled to a two phase, overlapping gate CCD.

socket attached to a standard prism coupling optical mount. A macroscopic view of HeNe laser light coupled into the optical waveguide through a prism coupler[5] is shown in Figure 4-a. The bright area on the left is a top view of the prism illuminated by scattered light, while the dark area in the center is a clamp pressing the prism against the surface. The streak of scattered light is approximately 125 μm wide and corresponds to the light beam which had been externally focused propagating until it reaches the detector region. Bonding wire leading from bonding pads on silicon to connections on the package is illuminated by scattered light. The detector array is located between the termination of the streak of light and the bonding pads. Because the magnification in Figure 4-a is considerably less than that in Figure 3, details of the CCD detector array are not resolvable. Note that there is no visible indication of excess scatter occuring in waveguide-detector coupling. Figure 4-b is an oscilloscope trace of the signal emerging from the CCD corresponding to the laser excitation in Figure 4-a. Differential amplification of the signal was used to eliminate some of the pickup from the clock pulses.

The device was operated with a two-phase clock producing overlapping pulses in the 100 KHz frequency range. Counter circuitry synchronized to the clock was used to control pulsing of the transfer gate so that this gate was turned on only after charge in the CCD shift register had been completely shifted out. Counter circuitry was also employed to provide a suitable electronic input for electronic evaluation of charge transfer efficiency. Charge transfer efficiency can be evaluated by serially injecting several low duty-cycle rectangular pulses with each separated by one clock period.[7] By carefully noting the degradation of the leading and trailing edges of the pulse train, information regarding transfer efficiency can be inferred. For the devices fabricated we determined a transfer efficiency of .993 per double transfer. Although this value is adequate for performance of our 19 stage device, higher values can be obtained. Good charge transfer efficiency requires very sharp lateral potential barriers.[8] Although the purpose of the channel stop diffused regions is to provide such

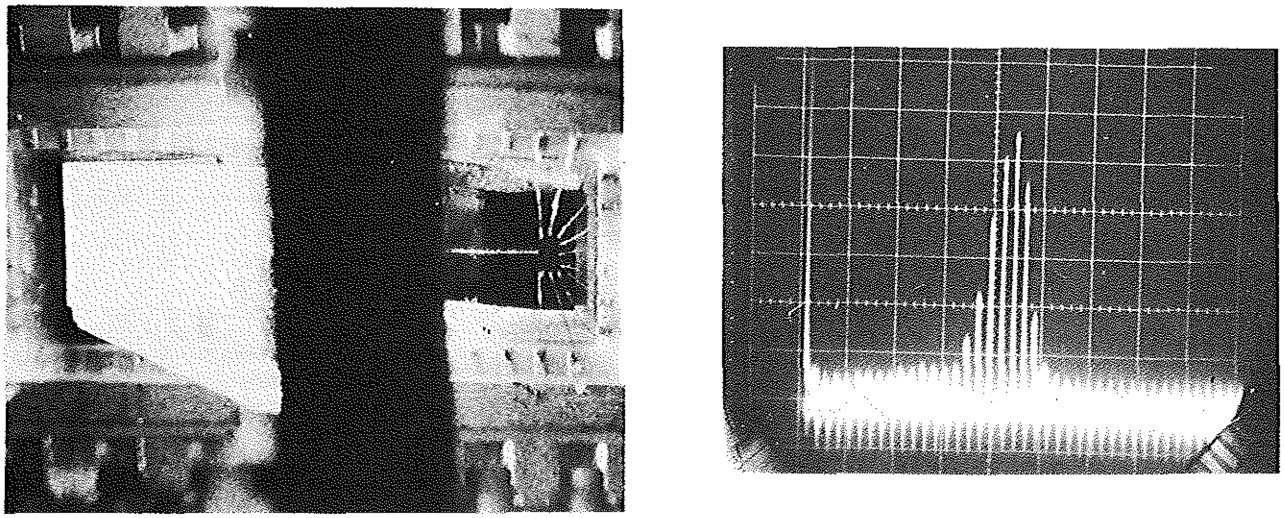

Figure 4. (a) Light propagating in an optical waveguide from the prism coupler to the integrated CCD detector array. (b) CCD output signal corresponding to illumination shown in (a).

n+ barriers, the device processing sequence we employed involved a high temperature thick gate oxide growth step after the channel stop diffusion. Further diffusion thus would occur during the oxide growth, resulting in more gradual lateral barriers. Evidence that this was indeed occuring was obtained from the transfer efficiency measurements in that larger values of bias charge than usual were required to eliminate fixed transfer loss.[7] The problem can be overcome by using ion implantation for channel stop doping and altering the processing sequence.

III. APPLICATIONS

The integrated optical waveguide and charge-coupled device (CCD) linear imaging array structure is expected to find many applications in integrated optical signal processing device structures. Optical signal processing using an integrated optical format combines the advantages of parallel processing with those present in an efficient, compact, and economical device. Parallel processing occurs when information is imparted to the transverse spatial distribution of an optical wave. Appropriate modulation and processing techniques include highly-efficient and wide band acoustooptic deflection,[9] electrooptic deflection,[10] and one-dimensional spatial Fourier transformation performed by an optical waveguide lens.[11]

For example, integrated optical acoustooptic deflection, optical waveguide lenses, and an integrated waveguide-detector such as described herein can be used to perform wide band spectrum analysis of electronic signals by employing the configuration shown in Figure 5.[4]

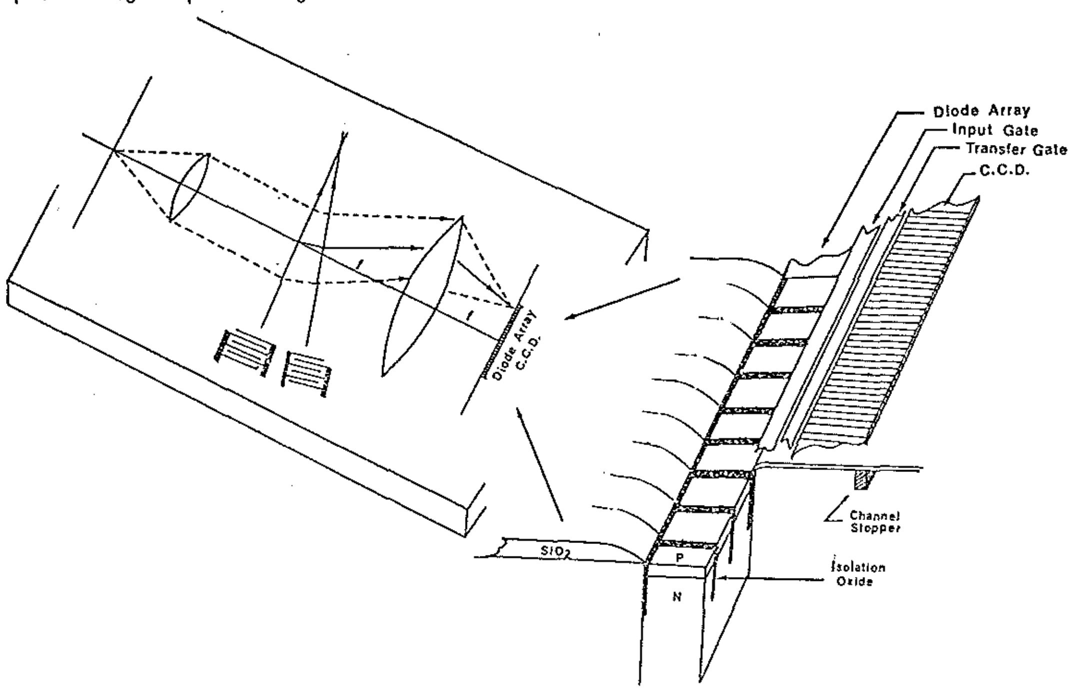

Figure 5. Integrated optical spectrum analyzer configuration.

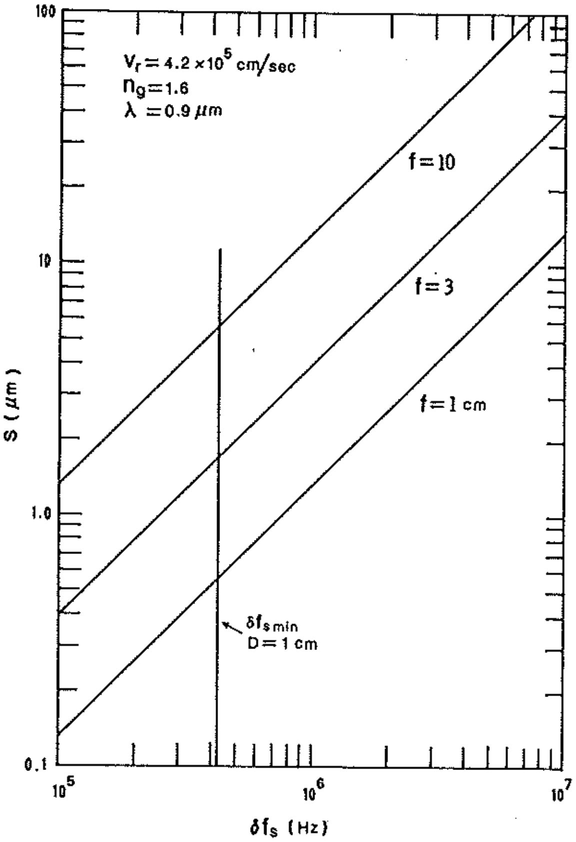

Figure 6. Detector array center-to-center spacing as a function of spectrum analyzer frequency resolution.

Coherent laser light propagating in a thin-film waveguide is expanded and collimated prior to being incident on a surface elastic wave which has been excited by the incoming signal. Surface elastic waves can be excited efficiently on silicon using a ZnO film in the transducer region.[12] Diffraction of light by the surface elastic wave occurs in such a way that light is diffracted at different angles corresponding to different signal frequency components. The signal frequency range of the spectrum analyzer corresponds to the bandwidth of the surface elastic wave transducer configuration. For a range of signal frequencies and wave intensities, the deflection angle is linearly proportional to the signal frequency and the diffracted light amplitude is linearly proportional to the signal surface elastic wave amplitude. A waveguide lens is then positioned so as to perform a one-dimensional Fourier transform. Signal spectral information which is represented by the angular composition of light emerging from the surface elastic wave region then becomes represented by the transverse spatial variation of light in the Fourier transform plane. The intensity of the light spatial distribution in the transform plane corresponds to the signal power density spectrum and can then be converted to an electrical signal by means of a detector array. With the presence of a CCD in the detector array, transformation of the electrical signal from a parallel format into a serial format occurs in a natural and simple way.

Information capacity of integrated optical signal processing devices will be limited by beam diffraction or array resolution and detector dynamic range.[4] In particular, the nature of acoustooptic deflection and of the Fourier transform property of lenses causes the optical diffraction pattern in the lens transform plane to be displaced by a distance s for a signal frequency deviation δf_s, where[4]

$$s = \frac{f\lambda}{n_e v_r}\,\delta f_s \,. \qquad (4)$$

In (4) f is the lens focal length, λ is the optical wavelength, n_e is the waveguide mode effective refractive index, and v_r is the Rayleigh wave velocity. If the detector array in Figure 5 is spacing of s, then λf_s is the frequency difference which can be resolved by the spectrum analyzer. The relationship between center-to-center spacing and frequency resolution is illustrated in Figure 6 for several focal lengths and typical parameters. As expected, smaller center-to-center spacings are required to resolve smaller frequency differences. The vertical ine in Figure 6 corresponds to the diffraction-limited frequency resolution for a 1 cm. aperture. Once this assymptote has been reached, further reduction in detector center-to-center spacing cannot improve frequency resolution. As the presence of optical scattering will reduce both spectrum analyzer frequency resolution and dynamic range, integration of the array into the optical waveguide, and thereby minimizing scattering occuring in waveguide-detector coupling, will allow superior performance as compared with the use of an external detector array.

The integrated waveguide-CCD detector array may find additional applications based on its inherent property of parallel entry of signal information into a CCD shift register. Optical injection of parallel signals into CCDs offers significant advantages over electrical injection techniques, in that for the latter sophisticated stabilized charge injection circuits would likely be required for each entry tap. Furthermore, capacitive coupling limits both the proximity of adjacent taps and the maximum usable signal frequency for parallel electrical injection. Parallel optical signal injection using bulk optical waves along with a mask to implement a fixed tap weight transversal filter has previously been demonstrated[13] We anticipate that the use of integrated optical channel waveguide-detector structures could yield a programmable device with potentially a large channel density and almost complete channel isolation. Parallel integrated optical signal injection into CCDs may also find application in multiplexing, other types of programmable filtering, and memory devices.

IV. SUMMARY

Successful fabrication and operation of a linear CCD image array integrated into an optical waveguide structure have been described. Data have been presented with regard to the optimum array element size required for the light wave to be efficiently coupled into the detector region. Minimal excessive scattering in the region where coupling of light from the waveguide to the detector occurs was observed. The integrated structure that has been described herein is expected to serve as a basic element in integrated optical signal processing devices and to provide a method for parallel entry of information into CCDs.

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