APPLICATION OF COHERENT OPTICAL TRANSDUCERS TO OPTICAL REAL-TIME INFORMATION PROCESSING*

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INTRODUCTION

Interest in optical information processing stems from the never-ending effort to increase data handling capacity and to improve the interface with human senses. The manipulation of two-dimensional data in an image format and processing in a parallel organized integral transform distinguishes the optical analog computer from its counterpart—the electronic digital computer processing one-dimensional data in a sequential manner. The optical analog computer is admirably suited to performing linear operations such as matrix products, Fourier transform integration, and related correlations and convolutions. The photographic plate is usually employed as the input, memory, control function, and output to demonstrate optical information processing concepts.

The high signal sensitivity, large data storage, and wide spatial bandwidth are the attractive characteristics of a photographic emulsion. However, the time required to develop the latent image to obtain access to data is both dismally slow and cumbersome in comparison to electronic means. The chemical amplification encumbrance has led to consideration of thermoplastic and ultrasonic delay line recording as an alternative with the attendant compromise of serial data input. If optical analog computers are to compete with the developing electronic art, it is essential that the access time to current data be reduced to a small fraction of a second without compromise of data capacity. Furthermore, as real-time optical processing is achieved, a requirement for an optical adaptive capability will also arise.

Optical information processing systems require the functions of amplification, modulation, and detection to be performed throughout the signal spatial field. These functions can be effectively synthesized by an array of coherent optical transducers extending across the signal spatial field provided that the spacing between the individual transducers and their size are comparable to the radiation wavelength. A quasi-microwave approach to coherent infrared transducers and their arrays using microphotolithographic techniques is delineated.

OPTICAL OPERATIONS

The application of communication theory to physical optics has provided the foundations of optical information processing. The basic image transformation operation is illustrated in Fig. 1. The spatial signal is usually introduced at the object plane by coherent plane wave illumination of a photographic transparency. The resulting diffraction pattern in the Fraunhofer region is the Fourier transform of the spatial signal. The use of a lens (focal length F) permits the scaling of the Fraun-
Figure 1. Basic image transformation operation.

hofer diffraction region to a more convenient location at the focus of the lens. The Fourier transform of the spatial signal is formed in the lens image plane as a spatial frequency spectrum. For some applications, this spectral analysis is the desired output.

If various shaped aperture stops or blocks are inserted into the frequency plane, it follows that the output signal distribution from a second transform lens system will be altered by the filter impulse response. In fact, a lens acts as a low-pass filter. Matched filter enhancement of the signal-to-noise ratio can be demonstrated by inserting the complex conjugate of the signal transform into the frequency plane. The realization of a complex-valued spatial function in a photographic transparency is extremely difficult due to the required phase response.

An interferometric approach has been introduced to record complex functions on photographic plates. The addition of a reference wavefront as a carrier to the spatial signal produces in a photographic plate one component resembling a diffraction grating. The grating frequency is proportional to the angular separation between signal and reference beams. An interferometric recorded spatial filter of the symbol † is shown in Fig. 2.

The operations of convolution and correlation can be realized by further compounding the system with additional image transformations. The results

Figure 2. Interferometric spatial filter.
from use of the spatial filter, Fig. 2, for pattern recognition is shown in Fig. 3. The diffraction grating in the spatial filter has provided a convenient means to separate, by orders, the various components of the matched filter process. Using the symbol  as the input, three components are observed in the output: 1) the input convolved with the filter impulse response, 2) a crude image reconstruction, and 3) the input cross-correlation with the filter conjugate impulse response—indicative of recognition.

Gabor's holography has been rekindled anew with introduction of interferometric methods because of the vivid three-dimension reconstruction of the scene with parallax. A hologram is a spatial filter for a particular scene when coupled with the transform in a human eye. The hologram, when illuminated by a delta-function distribution (point source), which has a uniform spectrum, allows passage of only those spatial frequencies which will form the reconstructed wavefront and thus the desired image. For optical pattern recognition, the holography process is inverted so that the unknown object serving as a source illuminates a spatial filter producing a single point image (correlation point). Figure 3 also shows the symbol reconstruction using the spatial filter in Fig. 2 as a hologram. Both the real and virtual images of the symbol are apparent.

Current optical pattern recognition techniques require a rigorous matching of the spatial filter and the input. Factors such as position, scale factor, orientation aspect, and inversion severely compromise the recognition fidelity. Some problems can be solved by restricting the list of symbols to a particular style.

Consider the problems of recognition and tracking of hurricanes in cloud patterns recorded by satellites. Pattern characteristics peculiar to the hurricane spiral and invariant with observation conditions are obviously obscured by noise. Therefore, during the learning phase it will be necessary to assemble a large catalog of spatial filters from successive cross-correlations of known hurricane spectra. From the catalog of spatial filters, a characteristic set are selected and the decision criteria established. The correlation of unknown cloud patterns with the stored filters provides a basis of comparison in the recognition process. Of the utmost importance is the optimization of the recognition process by including an adaptive feature; that is, a measurement of the correlation point amplitude ratio with respect to the side lobe skirt level and distribution to alter the filters within the classification set. This means that techniques must be developed to alter the spatial filters dynamically so that they can change their functional properties with time in accordance with new data.

**SPATIAL MODULATOR**

The requirements of a spatial modulator to dynamically implement optical spatial filters are briefly outlined. A spatial modulator is schematically illustrated as an array in Fig. 4. The functions of amplification, modulation, and detection must be performed throughout the aperture in a linear fashion with respect to the control signal, while the quantized elements of the array must operate independently without crosstalk. A spatial modulator may operate in either a transmission or reflection mode and may alter either the amplitude or phase characteristic.

Factors which influence the quantization of the spatial modulator into an array are available from antenna theory. Some of these are:

1. The half period factor ($T$) of the highest spatial frequency component must be greater than the array period which must be greater than one-half the wavelength. ($T/2 > s > \lambda/2$)
2. The array factor giving rise to a grating lobe period must exceed the angular diameter of the lens (see Fig. 1) for an unambiguous operation. \((\lambda/s \geq D/F)\)

3. The beamwidth of a single element must exceed the angular diameter of the lens to be included within the integration. \((2\lambda/d \geq D/F)\)

4. Random phase and amplitude errors should be minimized to preserve the dynamic range in the optical system.

A wide variety of bulk interaction phenomena exist to alter the optical properties of materials by application of electric and magnetic fields or by mechanical stress. Most of these interaction phenomena are weak—even in high fields. It is also difficult to induce from the outside the spatial perturbations. Therefore, a bulk spatial modulator without quantization and with a significant spatial bandwidth is impractical. However, heteroepitaxial semiconductor, ferroelectric and ferromagnetic materials imbedded with conductor arrays are a promising approach.

Current integrated circuit technology provides an approach to quantize the array. Moss has analyzed various methods of modulating infrared radiation using semiconductor materials which will respond rapidly. A quasi-microwave approach using semiconductor diode junctions which may be assembled into arrays for modulation and amplification will be discussed in the following sections. The depletion layer in diodes is considered as an optical transmission line where its length is controlled by the applied voltage. Current integrated circuit technology is now becoming interconnection-limited. The interconnection limitation also prevails in an optical spatial modulator. However, there are several means to circumvent the problem. A variety of photoeffects occur in semiconductor material and junctions when the illumination radiation wavelength is shorter than the band edge. Of particular interest here is the photovoltaic effect in a junction. The electron-hole pair created by absorption near the junction is separated by the internal field at the junction and thus alters the optical properties of the depletion layer for radiation longer than the band edge. Through this process, it should be possible to control the optical spatial modulator diode array by illumination of the array with a second beam containing the spatial control signal. A similar control of a parametric amplifier array is also possible through pump excitation. The photodetector array art is currently well established and need not be discussed.

### PASSIVE INFRARED WAVEGUIDE

Implementation of an optical spatial transducer requires interconnection by a waveguide which preserves the state of polarization and mode of propagation. Optical dielectric waveguides of circular and planar cross section have been demonstrated and reported in the literature. Control of a specific mode of propagation is best accomplished in transmission line with dimensions comparable to the wavelength. The binding of the electromagnetic field to the dielectric structure depends upon the relative index of refraction of the transmission medium being greater than the surrounding environment. An active and a passive infrared waveguide structure is illustrated in Fig. 5. The rectangular dielectric image line supported on a reflecting surface is ideally suited for coupling and integration with optically active devices such as semiconductor junctions.

As an example of dielectric image line waveguide, Fig. 6 shows a “rat race” hybrid junction formed photolithographically. The dielectric is thermally grown silicon dioxide on a highly doped, polished silicon substrate. The dielectric cross section is 0.6 x 2.0 microns and thus is useful in the near infrared region.

The results of an experiment demonstrating the propagation of a single, lowest-order mode through
a dielectric image line waveguide are shown in Fig. 7. A cleaved cross section of dielectric image line (0.3 \times 1.2 micron cross section) and substrate was used for the photomicrographs. A Lloyd's mirror\textsuperscript{14} demonstration of interference fringes from the image line waveguide substrate is shown in the upper figure. The black region is the silicon substrate. The visibility of the fringes immediately adjacent to the substrate surface disappears because the light source is polychromatic and temporally incoherent. The presence of the waveguide is clearly apparent. The discontinuity in the fringes immediately adjacent to the substrate is due to the reflection from the outer surface of the dielectric image line waveguide. Note the subdued interference normal to the substrate resembling a Fraunhofer pattern. This is due to reflection from the dielectric image line waveguide at greater depth. The Lloyd's mirror illumination has been removed and replaced by a laser beam focused on the dielectric image waveguide in the lower figure. The transmission of a single mode through the waveguide is apparent. The circular radiation distribution is due to the dipolar field and the offset is due to the image phenomena. The substrate surface in the lower figure is indicated by some scattering at the focused input coupling.

ACTIVE INFRARED WAVEGUIDE

The depletion layer in a reverse-biased semiconductor junction diode will also guide optical waves.\textsuperscript{15-19} The free carriers in both n and p give rise to a solid state plasma having a slightly reduced index of refraction which confines light propagation in the depletion layer. In the back-biased planar diode, the thickness of the depletion layer sandwiched between n and p regions is controlled by the applied bias field and may be comparable to infrared wavelengths. A depletion layer waveguide is a useful active device because it provides an electronic means to control an optical wave phase velocity.
Obviously, a depletion layer used as a dielectric waveguide or resonator must be used in the spectral region where it is transparent. Most semiconductors are opaque in the visible region but are transparent in an adjacent infrared region. The intrinsic absorption is due to excitation of electrons across the forbidden energy gap. Lattice absorption and Reststrahlen bands exist in the far infrared region. The intervening region is comparatively transparent except for impurity and free carrier absorption. The differential index of refraction between the various layers in a depletion layer is comparatively small (10^{-2} to 10^{-4}) so that a wave field is weakly bound to the junction. Careful attention must be given to the selection of doping elements, their concentration and gradient, and the host lattice defects because fields surrounding the junction will cause absorption, diffraction, and scattering losses.

The work of Nelson and Reinhart\textsuperscript{20} is illustrated in Fig. 8 which shows the transmission through a GaP diode junction. Although their work exploited the linear electro-optic effect for modulation, this photograph vividly illustrates the changing dimensions of the depletion layer waveguide as a function of the applied bias field.

There are various other mechanisms to control the phase velocity in a depletion layer waveguide besides that of geometry. One is the electro-optic effect as above which leads to birefringence in the index of refraction. Another is the change of the index of refraction below the band edge of a semiconductor due to the dispersion associated with the
Franz-Keldysh effect. The Franz-Keldysh effect is a shift of the band edge to a longer wavelength because of the application of an intense electric field. The various considerations which enter into the use of depletion layer waveguide as an active optical circuit element suggest a III-V semiconductor material and a wavelength just short of the band edge.

A depletion layer boundary may also be used in the reflection mode as a movable mirror. A photo field effect transistor shown in the photomicrograph of Fig. 9 has been used for a demonstration experiment. An alloy gate contact and an etched channel were formed in the silicon slice between source and drain. The use of a preferential etch, the alloy junction technique, and oriented silicon has led to a high degree of parallelism between the etched channel surface and the depletion layer boundary. The pinch-off characteristic curve is indicative of the optical quality in the boundary planes and shows that the depletion layer can be driven into planar contact with the channel surface. Experiments show that the position of the reflected beam from the etched channel front surface and the depletion layer is controllable by the applied gate bias. Illumination of the channel also provided a control of the beam position.

PARAMETRIC INTERACTION

To provide optical amplification and a means to control an operation by an optical logic field, the characteristics and feasibility of infrared parametric interactions are discussed. Parametric interactions involve the mixing of one or more signal frequencies with an intense source called a “pump” producing sum and difference combinations. The Manley and Rowe\(^2\) energy relations show that there are two basic amplification mechanisms distinguished by the manner that the signal and pump frequencies are allowed to combine. Further discussion will be restricted to the difference combination which creates an effective negative absorption and results in a signal spectrum inversion.

Parametric interactions depend upon a reactive nonlinear phenomena. The nonlinear capacity of a varactor diode is due to the change of the depletion layer thickness. In the infrared region the carrier inertia prevents a similar response; however, the index of refraction of some materials have a nonlinear behavior in intense light. The polarization nonlinear susceptibility of III-V semiconductor compounds is several orders of magnitude larger than the piezoelectric crystals which have been used for optical parametric amplification.

Recently, positive gain has been realized in difference frequency parametric interactions by Wang and Racette\(^2\) using NH\(_4\)H\(_2\)PO\(_4\) and by Giordmaine and Miller\(^2\) using LiNbO\(_3\). They used a Q-spoiled solid state laser to pump a nonlinear crystal under index matching to efficiently produce a second harmonic. After filtering and collimating the beam, the harmonic was applied as a pump to a second nonlinear crystal to obtain quasi-degenerate operation. Birefringence in the crystal was used to balance the index of refraction dispersion to obtain matched phase velocities in their traveling wave circuit.

A quasi-microwave approach\(^2\) which differs significantly from the above investigations using piezoelectric crystals is currently under way. A planar section of depletion layer waveguide is used as a multimode resonator tuned to the signal idler and pump frequencies. The dimensions have been selected sufficiently small to prevent other undesirable resonances. The requirements for index matching in a traveling wave structure are removed by the use of low-order modes within the resonator wherein the fields and geometry defining the boundary conditions establish resonances which are algebraically related to the pump frequency. Within the constraints of known material technology, the available power and emission lines from continuous wave gas lasers, and for an acceptably high nonlinear susceptibility, gallium arsenide is preferred.
for diode fabrication. The current state of microphotolithography extends the quasi-microwave approach into the one-micron region and thus matches with gallium arsenide. Signal coupling to the amplifier will be provided by image line dielectric waveguide. An optical circulator is desirable to separate the input and output ports and provide a degree of stability. The development of heteroepitaxial ferrite and the associated photolithography completes the requirements so that a circulator may be integrated with the optical parametric amplifier.

CONCLUSION

It is hoped that a future report will verify that the quasi-microwave approach to optical information processing is feasible by demonstration of operation. At this point in the development, interest may be kindled for the extension into adaptive image processing by an array where spatial logic is achieved optically.

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