The role of the applied dc field for these materials is crucial and multi-functional. The field: (i) enhances charge carrier photogeneration quantum yield; (ii) stimulates transport of the photogenerated carriers; and (iii) forces a noncentrosymmetric alignment of $\chi^{(2)}$ chromophores *(in situ* poling). Indeed, as we found in our studies, a very efficient switching of the photorefractive response between "0" and "1" states of the diffraction efficiency can be effected in the millisecond time regime with the use of external field.[5]

The obtained photorefractive efficiencies compare well to the corresponding values for some of the known inorganic photorefractive crystals and, as research progresses, the efficiencies should scale up by a meaningful factor. Two areas of effort are important here; the use of better $\chi^{(2)}$ chromophores as well as more efficient poling techniques, and better control over the carrier trapping centers to produce higher amplitude space-charge gratings. Emphasis will also be put on increasing the beam interaction path length by using a guided wave geometry of the device.

ACKNOWLEDGMENTS

This research was supported by the U.S. Air Force Office of Scientific Research and by the National Science Foundation. We wish to acknowledge the collaboration with D.J. Williams and J.S. Schildkraut, Kodak Research Laboratories.

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Advanced Modeling and Simulation of Self-electro-optic Effect Devices

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Optical computing and photonic switching are new and emerging technologies for future parallel processing systems. Optically controllable switching elements based on multiple quantum wells (MQW), especially the self-electro-optic effect devices (SEEDs), are well-suited for applications in these areas and are now developed in different variants for mass fabrication of GaAs/AlGaAs integrated circuits (for an up-to-date overview, see Ref. 1).

As a basis for circuit simulations, we derived a new approximation of the photocurrent-to-voltage characteristics of the MQW diode.[2] The major mechanism behind this device is a clearly resolved exciton resonance at the absorption edge causing a strong nonlinearity in optical absorption. The exciton resonance shifts and broadens with electric field. This effect is used for modulating the reflectivity of MQW diodes and to obtain electrically and optically bistable circuits. Our approximation is the first that reflects the main nonlinearity and also the light-hole and heavy-hole resonance peaks. Henceforth, our approximation can be used to obtain more accurate dynamic models of the device for circuit simulations. These simulations are especially useful in designing of F-SEEDs[1] in which MQW diodes are integrated together with field-effect transistors to obtain circuits with greater logical functionality per optically controlled element ("smart pixels").

To simulate larger systems as a means of design verification and system performance evaluation, a generalized structure of an symmetric SEED with all (theoretically) possible input and output signals has been considered. This circuit can function as either a latch or as a logic gate performing the AND, OR, NAND, or NOR functions depending on the optical input signals used and on the preset pulse used to control the function. The behavior of this circuit has been described logically, and a logic model has been developed.[3] The logic model of the S-SEED has been used to study different system design approaches like the programmable logic array design and a newly developed method to design more compact S-SEED systems.[4]

Since simulations at different levels are of great importance for device development and system design, we hope that our work will contribute to the progress in the interesting area of optical computing and photonic switching.

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Optical Matrix Multiplier: Grating Degeneracy Recycled

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Grating degeneracy in volume holography has been a source of crosstalk noise during the readout of stored holograms. Special arrangement of input pixels[1] (*e.g.*, fractal sampling) is often needed to avoid crosstalk noise in optical storage, interconnections, and neural networks. Recently[2] the authors showed that grating degeneracy can be used to perform summation operations in a matrix-matrix multiplication. This is the first useful application of grating degeneracy ever reported.

Matrix-matrix multiplication is an important operation in many computational and processing applications. Direct matrix-matrix multiplication is extremely difficult in electronic computers because it is an $O(N^3)$ (where $N \times N$ is the number of elements in each matrix) operation that requires a long computation time for serial machines. Optical computing offers the advantages of parallelism and large capacity. Such capabilities have been successfully demonstrated in parallel vector-matrix multiplication. Although matrix-matrix multiplication can be performed as an extension of vector-matrix multiplication with wavelength or time multiplexing, these schemes are complicated by dispersion or time delay. Nonlinear optical techniques have been used recently in the parallel matrix-matrix multiplication.[3] These techniques require complicated alignment and suffer severe energy loss. Our new approach uses grating degeneracy in photorefractive media in conjunction with an incoherent laser array to implement parallel matrix-matrix multiplication. Specifically, multiplications are implemented by photo-induced index gratings whose amplitudes are determined by the interference between coherent beams, while summations are implemented by grating degeneracy.

In the new approach, both matrices A $(N \times N)$ and B $(N \times N)$ are placed at the front focal plane of a lens. At the rear focal plane of the lens, a volume holographic medium such as a photorefractive crystal is inserted to record the multiplication of the two matrices. Each matrix element is represented by the amplitude of a plane wave in the crystal. Both matrices are illuminated with a linear array of N lasers. These N lasers have the same wavelength but are mutually incoherent. As a result, only N^3 gratings $A_{ij}B_{jk}^*$ $(i, j,k = 1,2, \cdots N)$ are written in the nonlinear medium. In addition, the matrices are oriented such that the gratings $A_{ij}B^*_{jk}$ for $j = 1,2, \cdots N$ are degenerate (*i.e.*, have the same grating wave vector). Thus grating degeneracy leads to a natural summation of the N terms $A_{ij}B^*_{jk}$ with $j = 1,2,\cdots N$. And the readout of the N^3 gratings leads to a matrix of only N^2 elements that are exactly the elements of the product matrix $C = AB$.

The method described above has been implemented experimentally using a $LiNbO_3$ crystal. Experimental results are in excellent agreement with theoretical predictions. One example is shown in the figure below. To our knowledge, these are the best experimental results ever reported on optical matrix-multiplication.

Theoretically, the above system is capable of handling large matrices such as those with 1000×1000 complex elements with a computation speed of 10^{12} operations per second with a moderate power level. Such an optical matrix multiplier, with its large capacity and parallelism, can potentially be used in optical computing, photonic switching, and optical neural networks.

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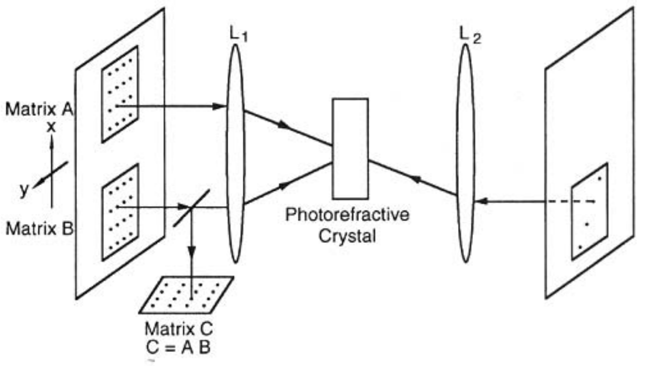
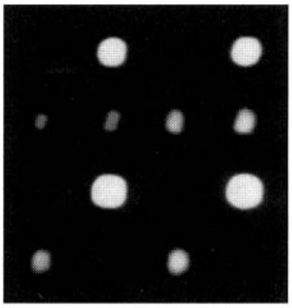


Example:

$$\begin{pmatrix} 1 & 0 & 1 & 0 \\ 1 & 1 & 0 & 0 \\ 1 & 0 & 1 & 1 \\ 0 & 1 & 0 & 0 \end{pmatrix} \begin{pmatrix} 0 & 1 & 0 & 1 \\ 1 & 0 & 1 & 0 \\ 0 & 1 & 0 & 1 \\ 0 & 1 & 0 & 1 \end{pmatrix} = \begin{pmatrix} 0 & 2 & 0 & 2 \\ 1 & 1 & 1 & 1 \\ 0 & 3 & 0 & 3 \\ 1 & 0 & 1 & 0 \end{pmatrix}$$

Experimental Results:

$$\begin{pmatrix} 0 & 2.0 & 0 & 2.1 \\ 0.9 & 0.9 & 1.0 & 1.0 \\ 0 & 3.0 & 0 & 3.0 \\ 1.0 & 0 & 1.0 & 0 \end{pmatrix}$$



Schematic diagram for the optical matrix multiplier and an example of the experimental results.