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Optical Matrix Multiplier: Grating Degeneracy Recycled

BY CLAIRE GU, PENNSYLVANIA STATE UNIVERSITY, UNIVERSITY PARK, PA., AND SCOTT CAMPBELL AND POCHI YEH, UNIVERSITY OF CALIFORNIA, SANTA BARBARA, CALIF.

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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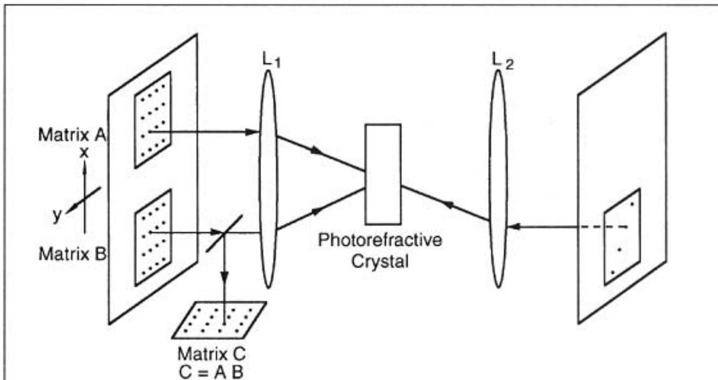
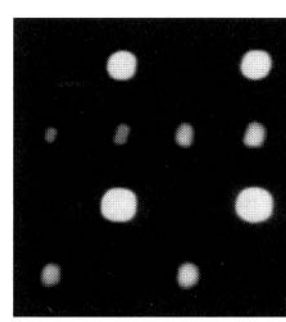


Example:

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

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.