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HOLOSWITCH - PHASE I

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1.0 INTRODUCTION

The purpose of this Phase I SBIR contract was to invent ways of using "switchable holograms" to change from one optical interconnect pattern to another with great speed. That is, we sought to combine the high flexibility in design and high diffraction efficiency of classical holography with the reprogrammability of the far-less-efficient real time holography methods of four wave mixing, three wave mixing, etc.

We have solved this problem in many separate and wholly satisfactory ways. A Phase II proposal to develop the best of these solutions is being submitted along with this report.

The report organization is historical. That is, it follows the path of our thought as it evolved toward the "ultimate" solution. This historical matter is important in that it sets the stage for recognizing the superiority of our final design over earlier versions.

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2.0 THE "WHYS" OF HOLOGRAPHIC INTERCONNECTS

Three "whys" will receive some attention here. Why optical interconnects? An excellent recent paper¹ answers that question exhaustively and convincingly. Optical interconnects are here already in high level systems. They will penetrate down to board-to-board and chip-to-chip levels. They may even be used for within-chip interconnects. Why should the interconnects be rapidly reprogrammable? The reasons include flexibility, compactness, robustness, and cost. Why use holograms for optical interconnects? They are the most flexible optical element known. They are cheap, light, compact, and efficient. Chromatic effects with anticipated sources are minimal. The main problem with "classical" holograms is that they are not generally switchable.

3.0 DESIGNING AN INTERCONNECT HOLOGRAM

Before we start switching from one interconnect hologram to another, we should have in mind a design for a single fixed interconnect hologram.

We imagine a nondescript array of M solid state sources (LEDs, LDs, etc.) each being modulated with its own signal. Likewise we imagine an array of N fast detectors. We would like, in general, to specify for each source (s_i , $i = 1, 2, \dots, M$) one or more particular detectors (d_j , $j = 1, 2, \dots, N$). For now our objective is to implement a particular M to N pattern holographically. For simplicity we will ignore the very real problems of beam shape and source beam direction and simply postulate beams of the shape and direction we need.

The discussion will follow the logic path pictured in Figure 1. Decisions to be made are entitled 'Switching?', 'Volatile?', 'Random Access?', and 'Angularly Multiplex?'.

3.1 Switching?

The option presented here is either to have a fixed or a changing interconnect pattern. It has been shown¹⁻² that a changing interconnect pattern is essential to the ever shrinking IC component in order to take full advantage of its huge computing capacity. Without flexible interconnects, the capacity of VLSIs will be ultimately limited by the pin out problem, that is, the input/output connections require more space than the integrated gates. A flexible interconnect chip at the VLSI output alleviates its input/output pin requirements.

3.2 Volatile?

Once the question of switching is answered, the task is to choose a switching mechanism. A volatile switching mechanism can be made to yield all

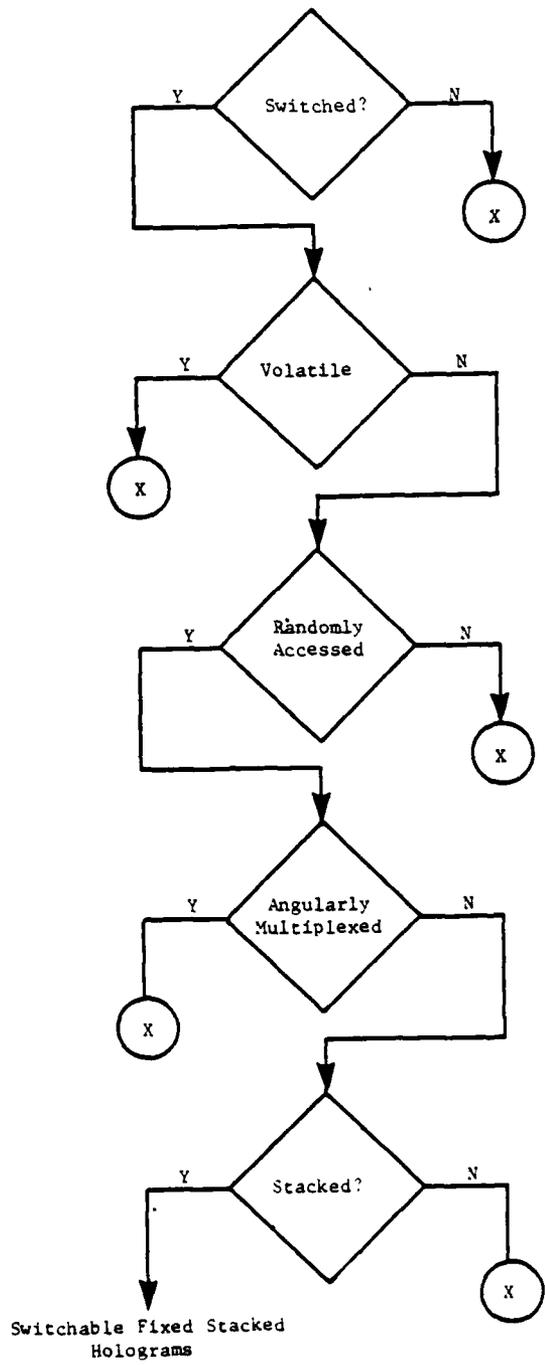


Figure 1. Holographic Interconnects Logic Sequence

possible M to N interconnect patterns (i.e., M x N or more). The hologram does offer this possibility in one element (in theory) and therefore volatility must be considered. The other option is a non-volatile interconnect pattern collection which holograms can offer as well. The non-volatile collection is a spatially multiplexed array of holograms, an angularly multiplexed multiple exposure hologram or a controllable access stack of holograms. A system of volatile holograms is expensive in terms of light efficiency, switching voltage, switching speed and size. This system, however, surpasses all other optical interconnect options in degree of globality or flexibility. Some aspects of volatile or, so called real time holographic systems are discussed below.

3.2.1 Real Time Holograms

An ideal real time hologram is formed in a material which can support an expose-erase-reconstruct cycle in a time period on the order of milliseconds. Materials do exist which are showing promise as real-time media. Five such promising materials are potassium tantalate niobate (KTN), thermoplastic film, LiNbO_3 , $\text{Ba}_{12}\text{SiO}_{20}$, and $\text{Sr}_{0.75}\text{Ba}_{0.25}\text{Nb}_2\text{O}_6$. The latter two are commonly called BSO and SBN.

3.2.1.1 Recording Media

The holographic recording capacities of these materials usually reflects a tradeoff between bias voltage and optical recording energy. A synopsis of research completed in the early '70s is presented to outline each material's operating parameters.

3.2.1.1.1 KTN - High recording sensitivity was accomplished by D. von der Linde et al.³ in potassium tantalate niobate (KTN) producing diffraction efficiencies of a few percent with a recording energy of $100 \mu\text{J}/\text{cm}^2$. The recording was accomplished using two-photon absorption of a single picosecond pulse with an externally applied electric field of 6.25 kV/cm. This sensitivity was reported as being comparable to holographic silver halide

emissions. The authors concluded that the large Δn observed experimentally in KTN as opposed to LiNbO_3 was due to a larger optically induced polarization and not due to a better electro-optic coefficient.

D. von der Linde et al. also noted that as a consequence of the cubic symmetry of KTN, the external electric field is required both for recording and reconstruction. They further noted that the material may be switched between the inactive and the active state by the field without affecting the stored information.

One problem reported was the difficulty in growing KTN with good optical quality. Further the dark conductivity of their samples (1975) limited the storage time to about 10 hours.

3.2.1.1.2 Thermoplastic film - A thermoplastic sheet is first electrically charged and then exposed to the laser fringe pattern which redistributes the charges through a photoconductor. The recording plate is then electrically charged a second time which increases the electric field across the thermoplastic wherever there was light exposure. Finally the recording plate is heated causing a permanent surface deformation dependent on the internal electric field, which is the desired hologram. The exposure process takes about 5 minutes. Voltage required separate from heating is $\sim 200 \text{ V/cm}^2$. A surface relief of $\Delta t = .3 \mu\text{m}$ will result on optical exposure of $\sim 20 \mu\text{J}$ for a diffraction efficiency of 15%. After 1000 cycles, the film must be replaced.⁴

3.2.1.1.3 LiNbO_3 - The first thick phase hologram was demonstrated in LiNbO_3 by Chen et al. in 1968.⁵ Chen proposed that the index of refraction was modulated via the electro-optic effect by the space-charge field which was produced by the spatial redistribution of electrons, which in turn was induced by light. This photorefractive effect occurs in a variety of electro-optic materials such as titanates, niobates, silicates, zirconates, "germanates", and a phosphate.⁶ Usually a large bias field is necessary. Using this type of medium, it is possible to record a hologram, store it and replay it or even to record and play simultaneously. A Δn of $\sim 10^{-4}$ can be obtained with a

1000 V/cm electric field applied normal to the optical path. Diffraction efficiency of these crystals is ~1-2%. Optical energy of $\sim 1\text{J}/\text{cm}^2$ is required.

3.2.1.1.4 SBN - This photo refractive material is similar to LiNbO_3 but exhibits 1) the capability to support many "stacked" 2-dimensional holograms, and 2) latent-active switching capability. Lower voltages of 1-5 Kv/cm are required. Holograms can be formed with optical energy of $\sim 5\text{ mJ}$ and yield a diffraction efficiency of $\sim 5\%$.⁷

3.2.1.1.5 BSO - Another material, $\text{B}_{12}\text{SiO}_{20}$ ($\text{B}_{12}\text{GeO}_{20}$) is grown as large crystals with good optical quality and shows a sensitivity of $130\ \mu\text{J}/\text{cm}^2$ for a diffraction efficiency of 1% .⁸⁻⁹ A lower efficiency (0.1%) is obtained without an applied field. In a crystal cube with volume 1 cm^3 a diffraction efficiency of 25% was obtained with 9 kV/cm. Also the dark storage time constant was about 30 hours. Huignard⁸ reports that the theoretical recording energy for 1% efficiency in 5 mm thick BSO with 6 kV/cm increases from $300\ \mu\text{J}/\text{cm}^2$ at a fringe spacing of $5\ \mu\text{m}$ to $4\ \text{mJ}/\text{cm}^2$ at a spacing of $0.6\ \mu\text{m}$.

3.2.1.1.6 Pockels Readout Optical Modulator (PROM) - Feinleib and Oliver⁹ reported a PROM device at Itek in 1972 using BSO with a transfer efficiency of 8%, an active area of $1.5 \times 1.5\text{ cm}$ with a contrast of 5000:1 and a spatial resolution of 300 cycles/mm. The charging voltage was 2900 volts and the recording sensitivity was $2.5\ \mu\text{J}/\text{cm}^2$ at 420 nm. Readout was accomplished using HeNe and GaAs lasers and a dark storage time of 2 hours was reported.

The PROM is operated with the applied electric field perpendicular to the optical aperture, utilizing transparent electrodes, and the stored image can be viewed between crossed polarizers using low-level red-illumination. The PROM is recorded by exposure to light which produces photoelectrons. The charges modulate the index which rotates the polarization of the readout beam.

Commercially available PROM's in 1978 had a 1" diameter, 1/10 wave smoothness, a 30 Hz cycle rate and a contrast ratio of 10^3 or $10^4:1$.¹⁰ However a smaller spatial resolution was reported of about 10 cycles/mm.

Casasent et al.¹¹ compared a U.S. built and a USSR built PROM in terms of sensitivity. The Soviet device uses a different crystal-cut in BSO resulting in 10 to 100 times greater sensitivity depending on the spatial frequency. Further the sensitivity as a function of spatial frequency rolls off as $1/f^2$ in the Soviet device as compared to $1/f^4$ in the American device.

3.2.2 System Configurations

3.2.2.1 Angularly Multiplexed Volatile Hologram

In this system a single hologram is multiply exposed in all desired interconnect pattern configurations (Figure 2). The interconnects thus encoded can be changed by re-exposure in the cycle time of the medium. For this system to succeed we must have "sufficient" angular selectivity. "Sufficient" is clearly a situation-dependent term, but even a crosstalk of 1% on a given detector from each of many "wrong" sources could become a major problem. Only very thick holograms can avoid this. Most highly selective thick holograms allow $\pm 1^\circ$ or more variation. This is a solid angle of about 0.001π steradians. An $f/1$ cone is about 0.5π steradians and therefore, such a device could have an M of ~ 500 . This interconnect could be made by exposing a transmission hologram with the desired pairs of sources on its input side. A detector on the output side occupies a position corresponding to the beam path of one of the pair of sources (see Figure 2). A lens is needed between the hologram and the detector matrix since the reconstruction point when reilluminated by the other of the pair of sources is virtual.

The hologram created by extreme sources in the source array diffracts light through 22.5° , the largest angle allowed assuming each source has an $f/1$ cone. If one dimension of the (square) matrix is d , and space is to be conserved, then a hologram of dimension d would be placed $2.6d$ down-stream, to allow the beams to propagate until they intersect appreciably. This hologram will only utilize 43% of the total light emitted by the two sources (see Figure 2).

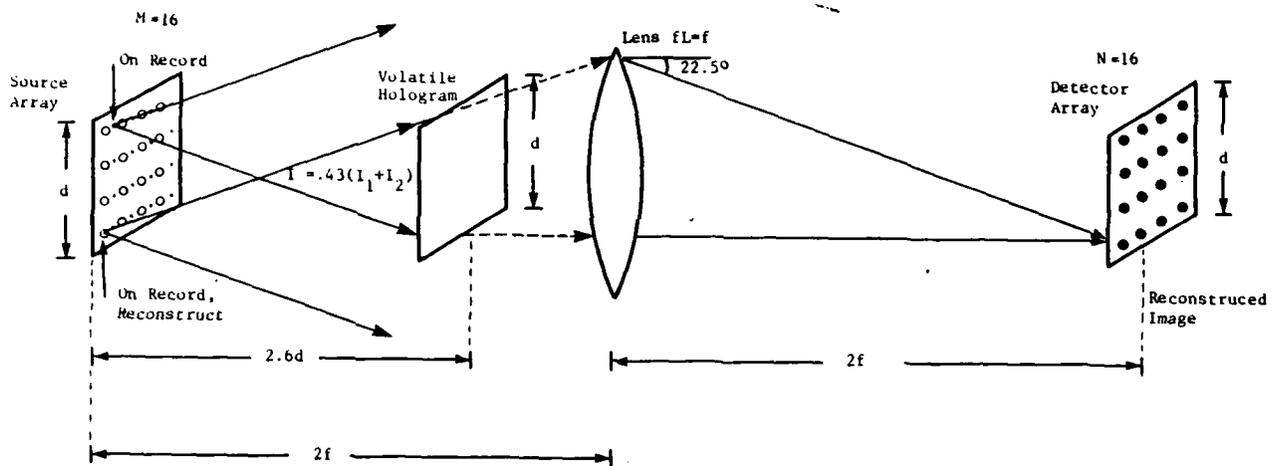


Figure 2. Optical Interconnect System with a Volatile Hologram. A hologram of dimension d will intersect a maximum fraction of 43% of the light in two $F1$ cones if placed a distance $2.6d$ from the source array.

One can imagine an optical system similar to Figure 2 with a 22 x 22 array of source pairs, a 22 x 22 array of detectors, a photorefractive crystal type hologram and a lens all of comparable cross-section, arranged in line with the over-all dimensions five times larger than it is wide. The optical efficiency for each cycle is $(0.43)(0.05) = 2\%$, assuming a 5% diffraction efficiency of the hologram and no cross-talk noise. This method is probably not satisfactory due to its large power consumption. Its size could be on the order of $\sim 15 \text{ cm}^3$.

To conclude, an N to M global angularly multiplexed interconnect requires 2N sources and M detectors. It consists of the two matrix arrays, a hologram, and a lens. It is inefficient and at the present we feel it has dubious feasibility.

3.2.2.2 Spatially Multiplexed Volatile Hologram

This option incorporates too many elements of other possible systems to fit into a single category. This is encouraging, since it represents a hybrid of the following options:

- Volatile
- Angularly Multiplexed
- Stacked
- Non-Volatile.

The system includes an array of sources, each accompanied by a real-time hologram formed in SBN or a similar material in which many interconnect patterns have been encoded, each of which may be activated by a specified voltage. In a sense, these latent holograms are stacked within the volume of the SBN in successive parallel planes. The optical system for reconstructing these pre-recorded latent holograms is much simpler than the completely global system described in Subsection 3.2.1. We envision each source illuminating a small $< 1 \text{ mm}^2$ SBN chip with voltages applied ($\sim 300 \text{ V}$ per chip) which select the connection to be active. By the above angular selectivity comments, we again specify 0.5π steradians and therefore again are initially constrained to 22 x 22 grids of sources, holograms, and detectors. The efficiency of

these holograms is limited by the characteristics of the SBN. We may be able to attain an efficiency of ~1%.⁷ No lens is necessary since these holograms were prerecorded to yield real images at the detector plane. Considering the propagation distance to the detector to be roughly the grid size, the optical part of this device would be about ~1 cm³.

From a system standpoint, the advantage of using SBN is in having prerecorded interconnect patterns from which any possible pattern can be chosen. However this degree of multiplexing (stacking) has not yet been demonstrated. The remaining system choices relate to prerecorded hologram patterns.

3.2.2.3 Volatile Holograms Conclusion

Real time holograms using any of the above technologies are possible, and with intensive development will become feasible for switching applications. However, these technologies are not mature and therefore offer no immediate solution to interconnect problems. We addressed the problem from the realistic standpoint of designing a piece of equipment which can be built. This is why we also present the concept of non-volatile holograms.

3.3 Random Access?

In consideration of paragraph 3.2, we made the decision not to recommend a volatile hologram solution to the interconnect problem.

The random/non-random logical step in our system plan presents the option of programmed or random interconnect pattern succession. References 1 and 2 both point out the need for random access-type succession. A programmed succession automatically limits system flexibility and, as we will show, does not necessarily simplify its implementation. The decision of succession, whether simple, as in programmed succession or complex, as in random succession is better performed in the VLSI, whose decision-making capabilities are exemplary, rather than in an interconnect device, which is only meant to provide the VLSI with an interface mechanism.

3.4 Angularly Multiplexed?

The system incorporating a non-volatile angularly-multiplexed hologram as an interconnect device has been discussed above (Subsection 3.2). There, the size and power consumption of such a device based on its volatility were predicted. Eventually, its efficiency was predicted - again however for a volatile medium.

In the case of a non-volatile angularly multiplexed hologram, all interconnect patterns must be recorded before the device is installed. Therefore, the quadratic efficiency dependence of an angularly multiplexed hologram must be considered. If L patterns are stored, then the efficiency will suffer proportionally to $1/L^2$. However, the efficiency of some thick holographic media approaches 80% and the recording can be done off-line resulting in an efficiency, if $L = 100$, of 0.008%. Further degradation will occur if the hologram exhibits cross-talk. This device is smaller, however, than the volatile device and is not inherently power-consuming. Therefore, except for its efficiency figure, the angularly multiplexed non-volatile holographic interconnect shows some promise. Limited efficiency, however, causes us to reject this option in consideration of our real-world criteria.

3.5 Stacked?

Because of the optical efficiency drawback of the angularly multiplexed hologram, we have chosen to try to find a better interconnect device concept. At this step we are again confronted with a choice; Do I spatially multiplex my holograms side by side or in a stacked fashion?

3.5.1 Side by Side

A serial method using a large diameter light beam and a spatial light modulator (SLM) is possible. The SLM chooses the interconnect pin by pin by opening a window to the appropriate hologram. The efficiency of this serial (slow) interconnect suffers as $1/M$, since only $1/M$ of the beam is used at any one time. An SLM-hologram combination was developed by Sawchuck and Strand.²

It operates as a logic sequence implementation device. The serial nature of the side by side multiplex option makes it unattractive, however, as an interconnect.

3.5.2 Stacked Holograms

A parallel device structure which can be semi-globally switched and which has reasonable efficiency is the most likely candidate for an honest development in consideration of real technology. Stacked holograms provide us with these criteria. Now, what is needed in stacking holograms is a method of activating only the one which carries the interconnect pattern of interest.

The stacking option we present incorporates fixed conventional holograms and electronically controlled polarizers. If holograms can be formed in such a way that incident light of orthogonal polarizations interacts differently, then the polarizer placed before the hologram serves to activate or deactivate it.

We identified two distinct configurations of an interconnect switch based on hologram stacking; polarization selective holograms and conventional holograms in combination with polarizing beamsplitters.

3.5.3 Polarization Selective Holograms

There are three options in solving the problem of making a polarization selective hologram. The first two cite recent research into the problem and the third is our own idea which has yet to be demonstrated.

3.5.3.1 Photoanisotropic Media

Polyvinyl alcohol mixed with methyl orange has been shown¹³ to be an effective holographic medium which is sensitive to reconstruction beam polarization in a manner dependent upon recording polarization parameters. High diffraction efficiencies (35%) and extinction ratios were reported in holograms recorded with orthogonal circular polarizations and reconstructed with one of the recording polarizations.

3.5.3.2 Metallic Reflection Gratings

Much work is ongoing in an attempt to affect metallic ruled and holographic gratings towards higher polarization selectivity. The special designs are expensive and difficult to implement. One article¹⁴ compares ruled (blazed), lamellar (square wave), and sinusoidal (holographic) gratings. References cited in that article explains further the polarization selectivity of these gratings.

3.5.3.3 Conventional 90° Hologram

We can use a dielectric hologram with a 90° diffraction angle. This idea requires a diagram (Figure 3) for explanation.

The diffraction angle is 90°. Light polarized normal to the plane of the diffraction angle can be diffracted quite efficiently. Light polarized in the plane of the diffraction 90° angle and, of course, normal to the incident ray can not be diffracted at all. The reason is that no E field component in the incident ray is normal to the diffracted ray. Without such an E field no electromagnetic wave in that direction can exist.¹⁵ To get light in and out of such a hologram prism couplers are required. A particularly attractive unit is shown in Figure 4. These can be stacked and switched quite easily as shown in Figure 5.

3.5.4 Conventional Hologram/Polarizing Beamsplitter Combination

Another approach is to use birefringent prisms and polarization switches to switch light out of the incident direction and onto a hologram or array of holograms afixed directly onto one face of the prism. Figure 6 shows one such unit. These prisms are easily stackable, commercially available, and of excellent contrast (often 10⁴:1 or better).

3.5.4.1 Polarization Switches

The polarization switches can be any of the pockels, quartz resonant, or liquid crystal type. Pockels cells are very fast in theory (~500 MHz) but

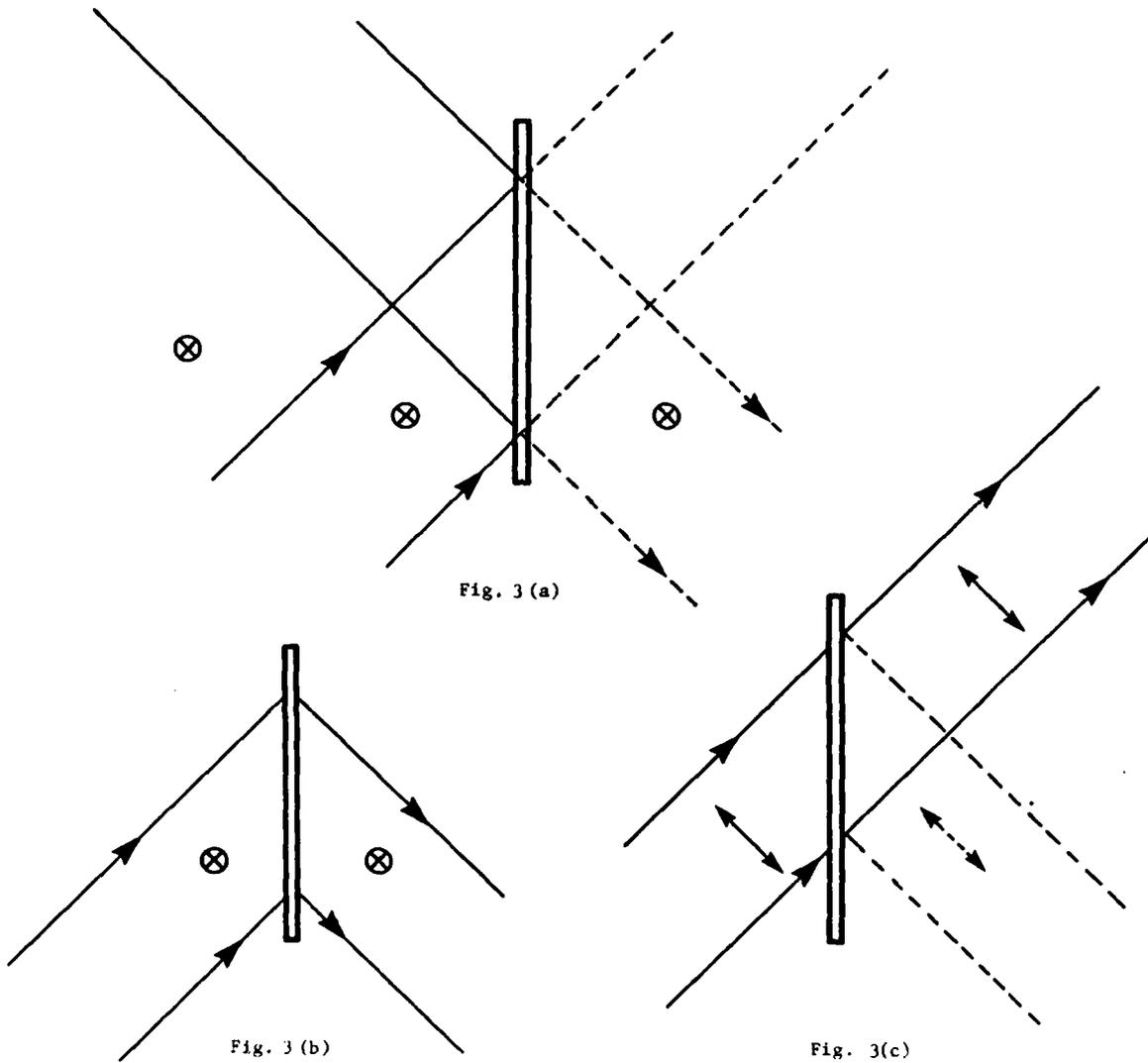


Figure 3. (a) Recording a 90° Hologram, + represents the plane of polarization is normal to the page. (b),(c) Reconstructing a 90° hologram. \longleftrightarrow represents plane of polarization in the plane of the page.

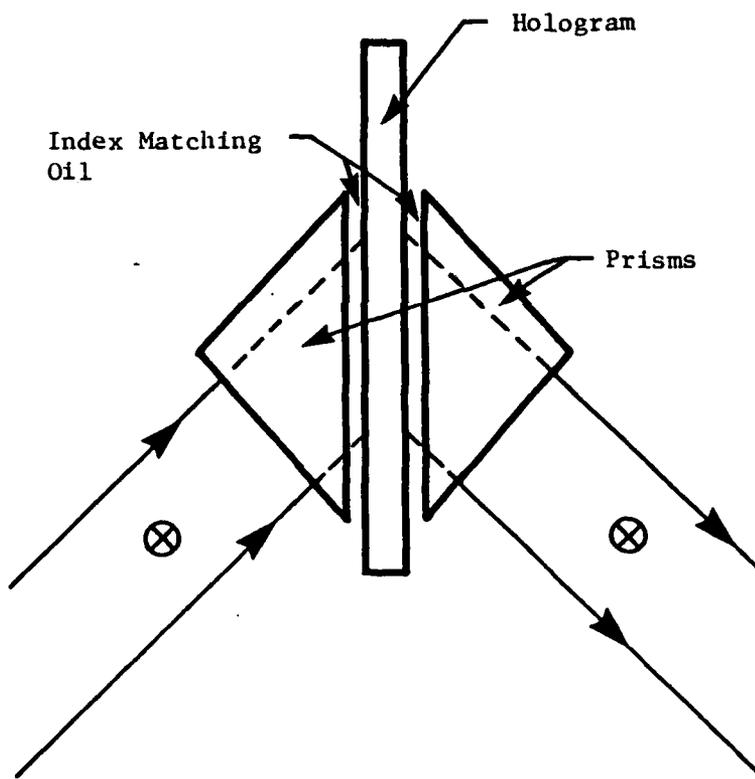


Figure 4. Switching Module Based on the 90° Diffraction Angle Hologram

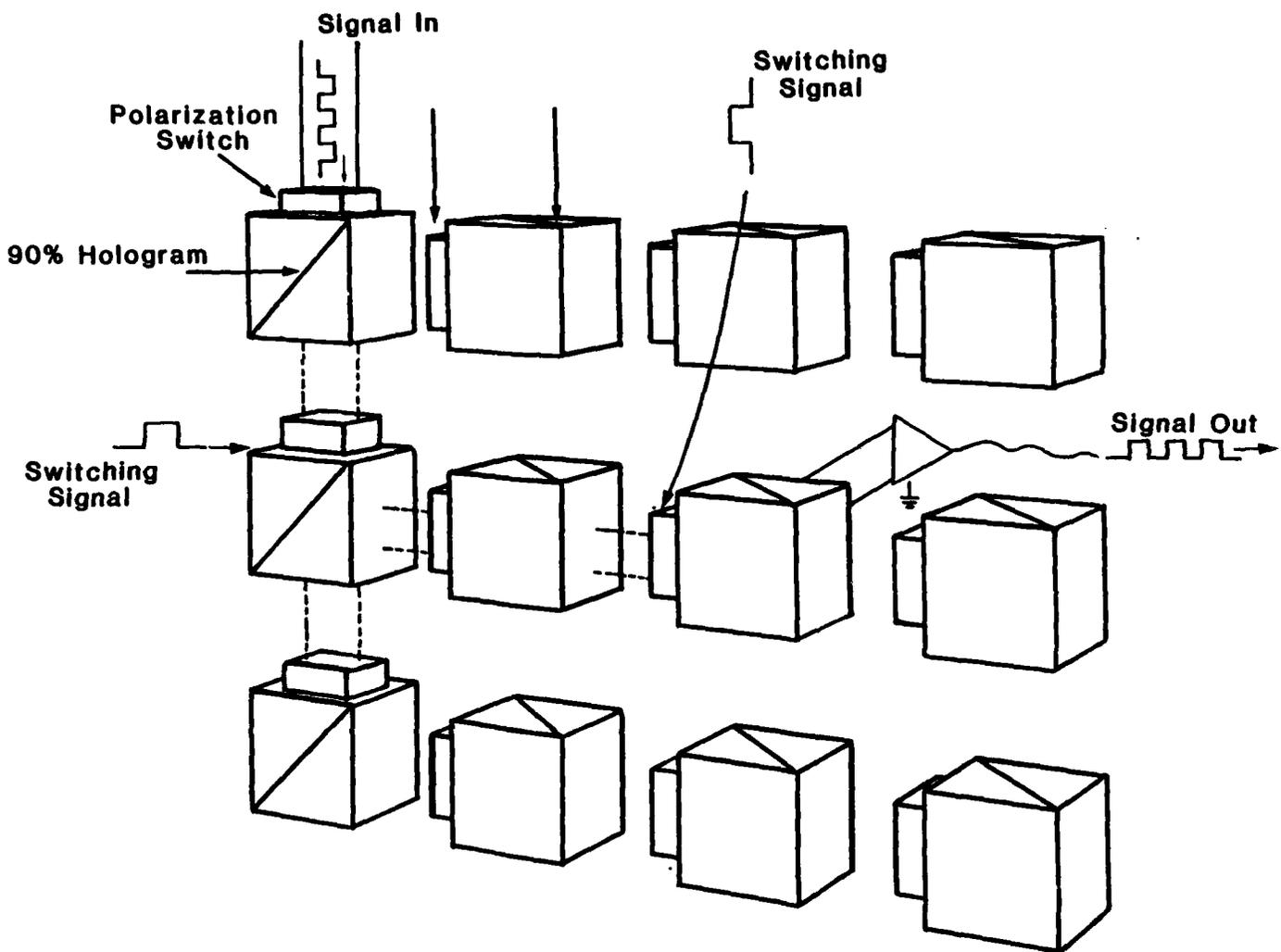


Figure 5. A 2-D Stack of 90° Diffraction Angle Modules. One Switching signal is needed per dimension.

suffer from a half-wave voltage requirement of hundreds of volts/cm. Quartz resonant crystals¹⁶ are promising as low voltage polarization switches but, due to the complex nature of quartz crystals, are little understood and could easily comprise an entire research project by themselves. In addition they require a large interaction length for high extinction ratio. Liquid crystal twist cells are proven low voltage polarization modulators which are fairly slow (~4 KHz) but are small and exhibit ~26 dB extinction ratio. In addition, liquid crystal cells have been demonstrated in conjunction with polarization selective beamsplitters for low insertion loss 2x2 cross bar switches.¹⁶

3.5.4.2 System Configuration

A system of polarization beamsplitters and liquid crystal polarization switches is shown by its component parts in Figures 6 through 9. This is the system (to be called the Aerodyne Holoswitch) which we will propose to demonstrate in our Phase II proposal. With this type of switch, the parallelism and low insertion loss of bulk optical components, is combined with the power efficiency and extinction ratio of a liquid crystal cell to steer a large number (M) of beams of arbitrary coherence towards any of a large number (P) of hologram matrices, each of which contains M sub-holograms which deflects the direction of its own particular beam. Input and output can be via fibers and collimating GRIN lenses, and two TTL control voltages (for a two dimensional array) can be applied in parallel to choose the one of P interconnect patterns as desired. The magnitude of M depends upon application and size constraints, not on switching time constraints. The magnitude of P determines the degree of globality¹ of the interconnect device. The assumption in designing an interconnect device with a specific degree of globality is that an electronic device is designed to communicate with other electronic devices in one of a finite number of specific patterns. Furthermore, as we discussed in Subsection 3.1, such completely global interconnects are not presently feasible because of the voltages required and the limited diffraction efficiency. In principle, any system which switches

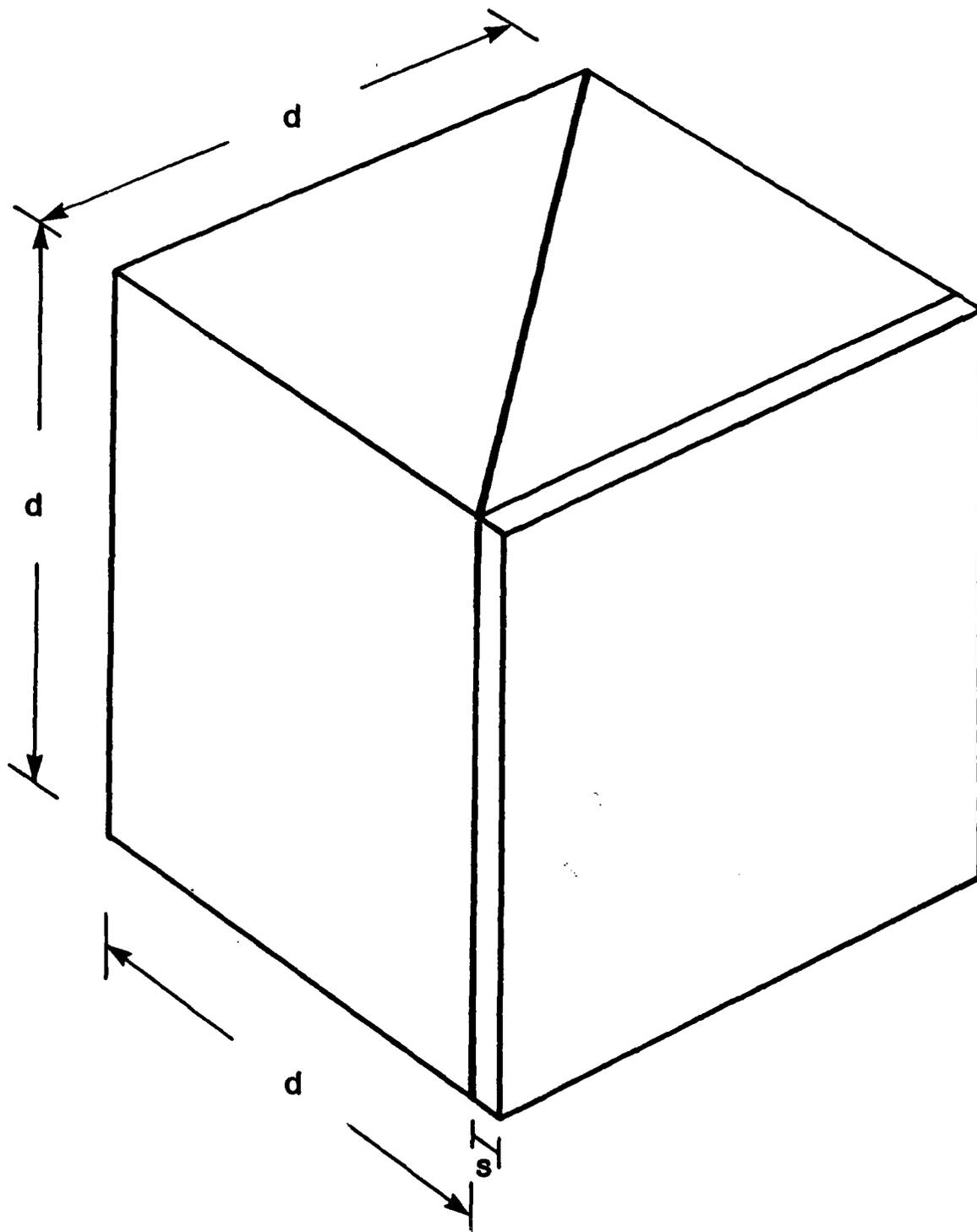


Figure 6. Beamsplitter, Polarization Switch Combination. s is the switch thickness, d , the cube face dimension.

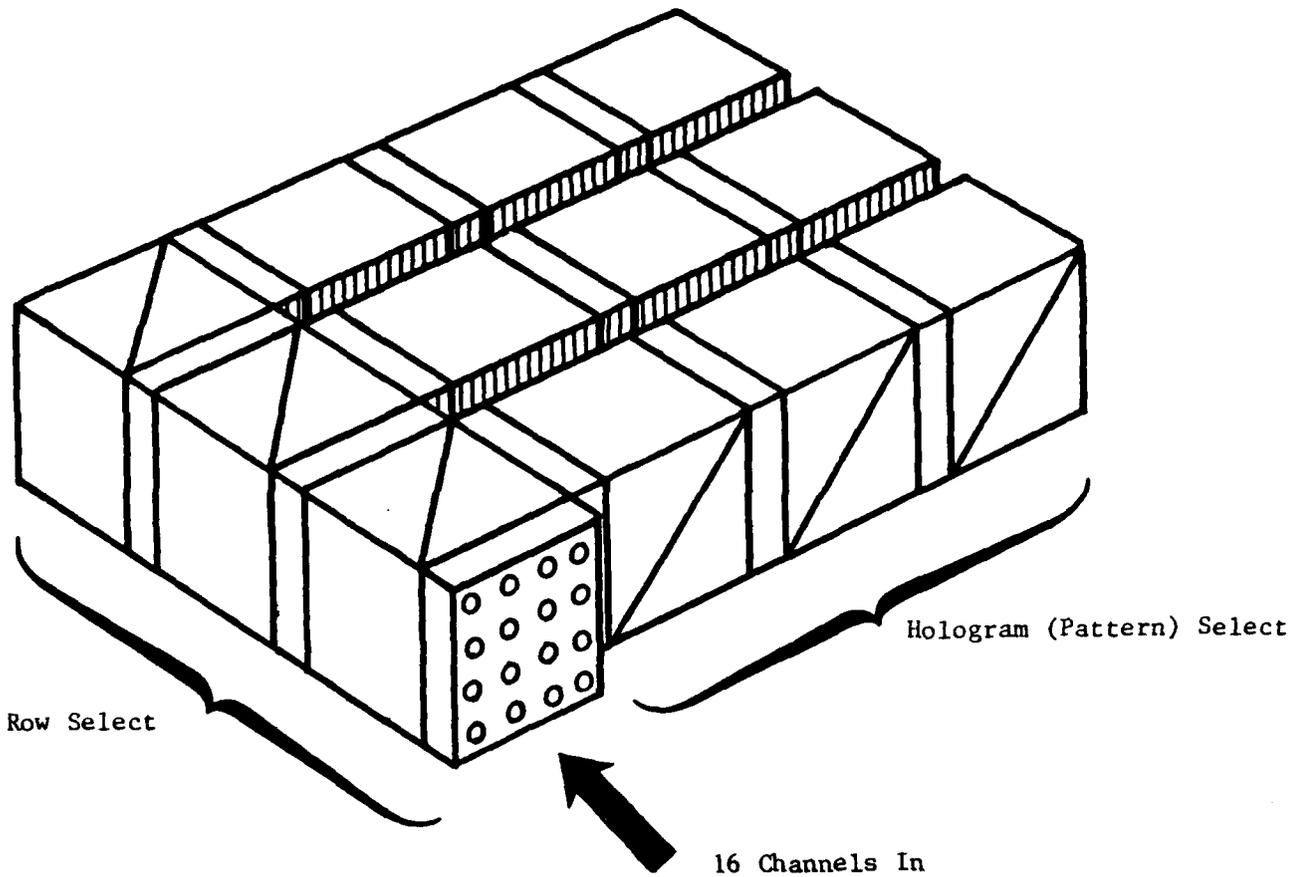


Figure 7. 3 x 3 Matrix Switch for Selecting $P = 9$ Interconnect Patterns of $M = 16$ Channels

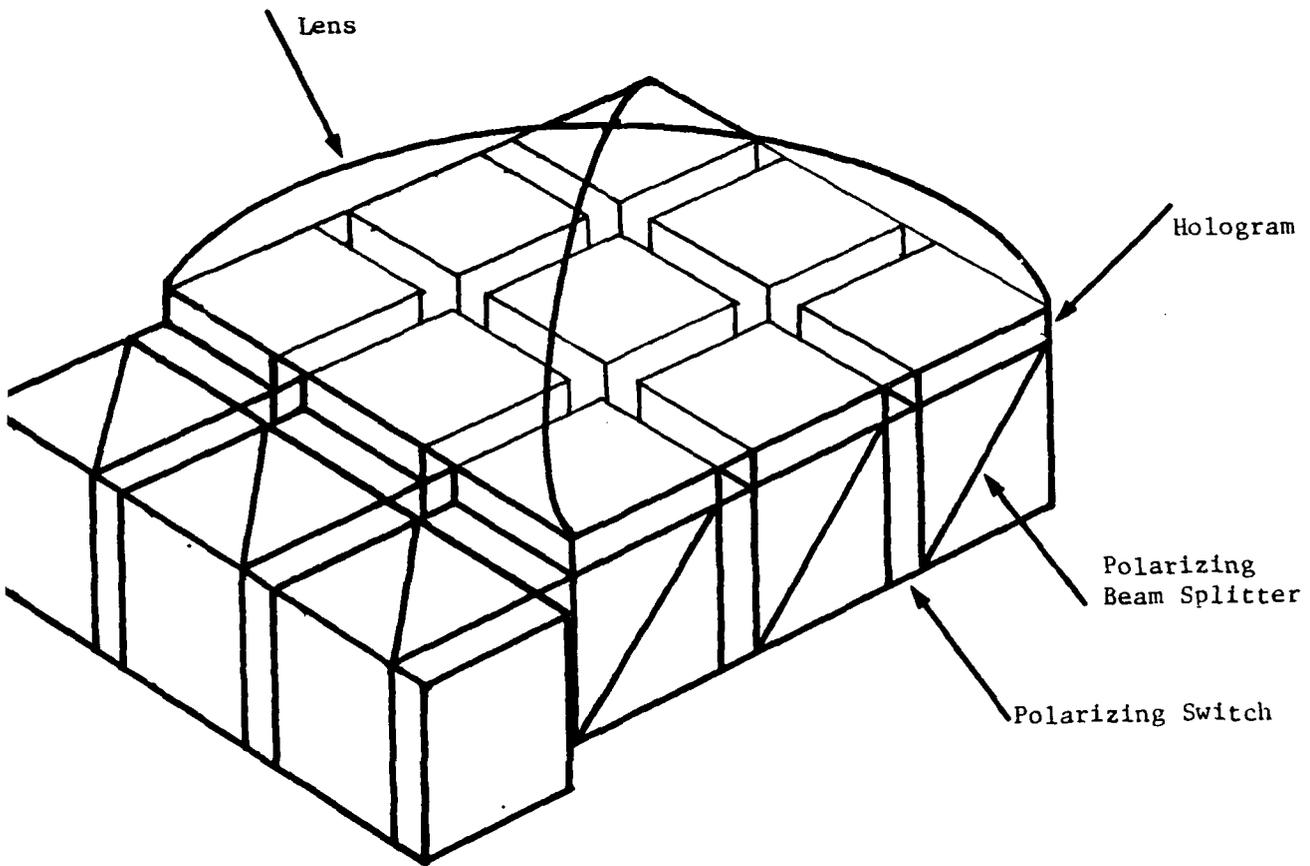


Figure 8. 2-D Array of $P = 9$ Interconnect Patterns. Two control voltages (TTL) are required to choose N_1 .

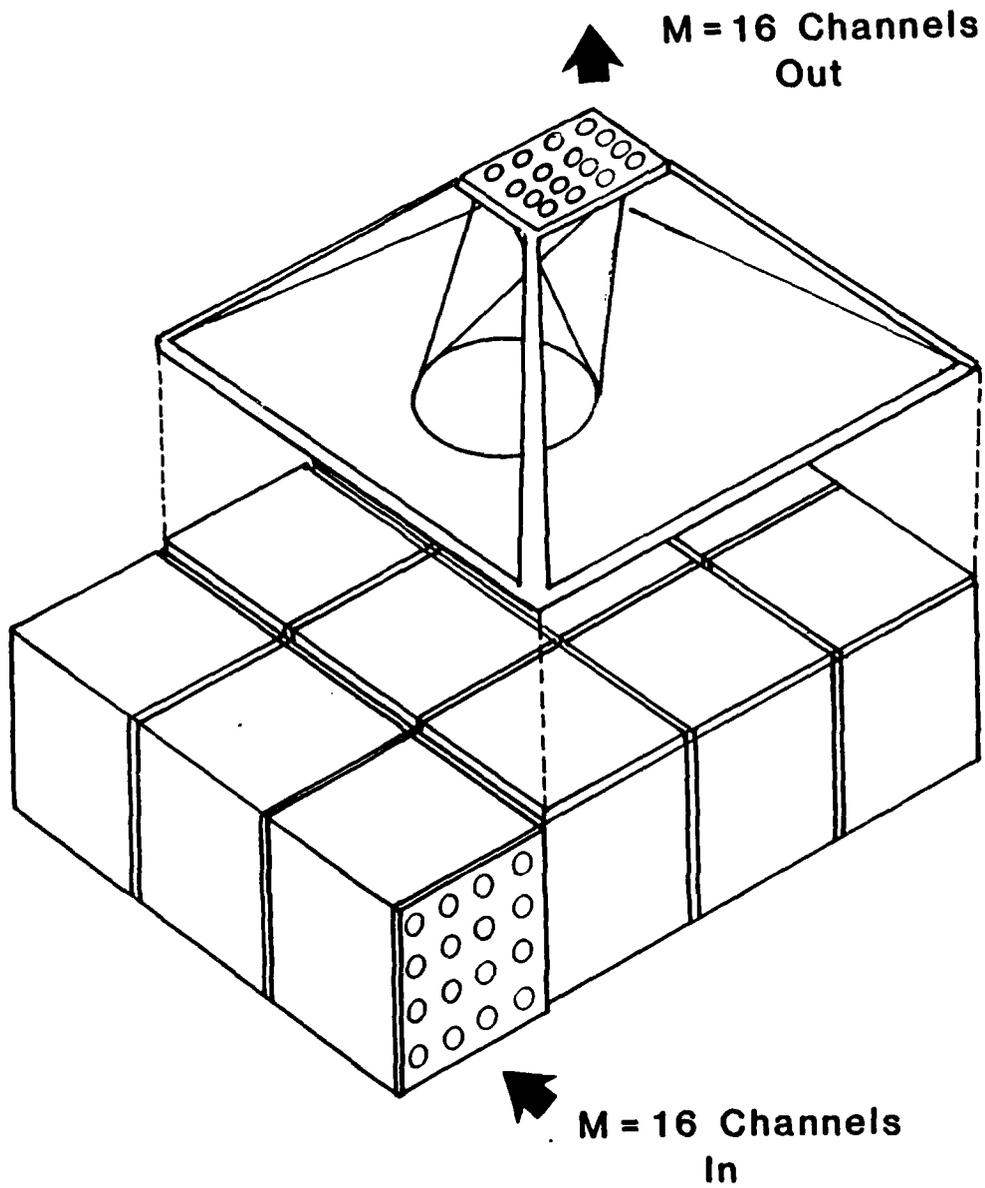


Figure 9. Final Assembly with Lens Lifted Showing Hologram Layer and Switches Roughly to Scale

an array of light beams in parallel towards a corresponding array of fixed holograms can accomplish high speed, TTL switched massively parallel interconnects. After considering all of the above interconnect options, we arrived at a simple and powerful device which we feel will considerably open up this field.

3.5.4.3 Example

Consider a 3×3 $P=9$ matrix switch. We start with $M=16$ 0.50 mm diameter beams of $\lambda = 1 \mu\text{m}$ in a 4×4 array. Such a beam will travel up to 5 cm with no appreciable divergence. Let the spacing between beams be 0.75 mm for safety. Clearly $3.75 \text{ mm} \times 3.75 \text{ mm}$ square contain them all conveniently. Using a 0.25 mm liquid crystal switch optically contacted to each 3.75 mm beamsplitting cube, we wind up with a unit cell (Figure 6) which is $3.75 \text{ mm} \times 3.75 \text{ mm} \times 4.00 \text{ mm}$. We can piece together 12 of these as shown in Figure 7. By applying two voltages, any one of the 9 (3×3) holograms will become operative. The $P=9$ holograms are deposited on the output face of each beamsplitter. For high efficiency, they are thick holograms, probably of dichromated gelatin or some polymer material in which the hologram is represented as an index modulation in the thick $\sim 100 \mu\text{m}$ emulsion. Each of the $M=16$ sub-holograms on the chosen beamsplitter produce the Fourier transform of its specified detector position with $\sim 80\%$ light efficiency. A lens makes the final interconnect as shown in Figure 8. The prism-switch array has dimensions $1.2 \text{ cm} \times 1.6 \text{ cm} \times 0.4 \text{ cm}$. A scale drawing is shown schematically in Figure 9 with the lens lifted to show the array of holograms. The output can be either electrical signals or optical fibers. Assuming a 2 dB insertion loss, the optical efficiency of this device is $(.63)(.63)(.80) = 32\%$, far better than any of the other possible systems discussed above.

4.0 CONCLUSION

A clear need for an alternative signal switching and routing technology, other than a purely electronic system has been outlined in Ref. 1. Many possible architectures for hybrid optical-electronic switching schemes for inter- and intra-VLSI chip communication were discussed. These schemes were presented to address problems presently confronting electronic designers such as:

- o Capacitive loading
- o E-field cross talk
- o Globality (multiplexing flexibility)
- o Clock skew

Optical solutions to the above and other related electronic problems will be in the areas of: transduction, propagation, and modulation.

In general, electric signals will be converted to optical signals, which will be propagated and switched in any of a variety of ways. Goodman et al. has made some generic suggestions - for instance, a clock signal can be distributed over a boardful of chips by a fiber optic data link in a straightforward manner; or data can be distributed in many different interconnect patterns using a Spatial Light Modulator mask and a spatially multiplexed hologram. Goodman's paper and private consultations with its authors motivated this research and therefore puts this work into perspective as a timely and essential first step towards assisting the next generation of large scale integrated digital hardware.

In Phase I, we have presented a feasible architecture for global VLSI interconnects. We have shown that holography can be applied to this problem and have chosen a specific method for doing so. Our chosen method has the potential for being inexpensive, small, power efficient, flexible, and

immediately compatible with highly integrated electronic components. A Phase II proposal to develop a working prototype of this semi-global interconnect switch is included with this Final Report.

Acknowledgement

We would like to acknowledge R. Soref of RADC/ES for his helpful discussions concerning switching techniques.

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