A Multi-Wavelength Optical Content-Addressable Parallel Processor (MW-OCAPP) for High-Speed Parallel Relational Database Processing: Architectural Concepts and Preliminary Experimental System

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Abstract. This paper presents a novel architecture for parallel database processing called Multi-Wavelength Optical Content Addressable Parallel Processor (MW-OCAPP). MW-OCAPP is designed to provide efficient parallel retrieval and processing of data by moving the bulk of database operations from electronics to optics. It combines a parallel model of computation with the many degrees of processing freedom that light provides. MW-OCAPP uses a polarization and wavelength-encoding scheme to achieve a high level of parallelism. Distinctive features of the proposed architecture include (1) the use of a multiple-wavelength encoding scheme to enhance processing parallelism, (2) multiple-comparand word-parallel and bit-parallel magnitude comparison with an execution-time independent of the data size or word size, (3) the implementation of a suite of eleven database primitives, and (4) multi-comparand two-dimensional data processing. The MW-OCAPP architecture realizes eleven relational database primitives: difference, intersection, union, conditional selection, maximum, minimum, join, product, projection, division and update. Most of these operations execute in constant time independent of the data size. This paper outlines the architectural concepts and motivation behind MW-OCAPP's design, as well as describes the architecture required for implementing the equality and magnitude comparison processing cores. Additionally, a physical demonstration of the multi-wavelength equality operation is presented.

1.0 Introduction

Databases are emerging as the most important ingredients in information systems. They have penetrated all fields of the human endeavor and are no longer limited to business-oriented processing. Database systems are becoming the backbone of (1) business, (2) computer-aided design and manufacturing, (3) medicine and pharmaceuticals, (4) geographic information systems, (5) defense-related systems, (6) multimedia (text, image, voice, video, and regular data) information systems, among many others.

Searching, retrieving, sorting, updating, and modifying non-numeric data such as databases can be significantly improved by the use of content-addressable memory (CAM) instead of location-addressable memory [1,2,3,4]. CAM-based processing is not only more akin to the way database users address their data (in parallel), but it is also faster than location-addressing schemes since the overhead cost of address computations is completely eliminated. Using the CAM model, the absolute address location of each object has no logical significance; all access to data is by content. Therefore, the CAM model is a naturally parallel form of database representation and manipulation with potential benefits in simplicity of expression (programming), storage capacity, and speed of execution. Unfortunately, large computers based on CAM have not been realized due to the difficulty and high cost of implementing them in conventional electronic technology. Until now, CAMs have only been included in computers systems as small auxiliary units [4,5,6]. Optics can alleviate the cell complexity of CAM-based storage cells by migrating their interconnects into the third dimension [7]. The high degree of connectivity available in free-space and fiber-based optical interconnects and the ease with which optical signals can be expanded (which allows for signal broadcasting) and combined (which allows for signal funneling) can also be exploited to solve interconnection problems.

A novel architecture called the Optical Content Addressable Parallel Processor (OCAPP) was demonstrated that implemented a limited set of high-speed database operations [2,8,9,10]. The architecture combined a parallel associative model of computation with high-speed optical technology. The implemented operations were divided into parallel equivalence and relative magnitude searches, and were accomplished using an intensity and polarization-encoding scheme [11]. The parallel algorithms used in OCAPP can be considered one-dimensional such that a single comparand (search argument) is matched against an entire database in constant time (O(1)). However, if n number of comparands are to be compared (a two-dimensional operation), the execution time increases from O(1) to O(n). Multi-comparand comparison can be accomplished in constant time by stacking replicates of optical units, but this is a very inefficient use of space and resources. The implementation of efficient two-dimensional database operations requires that an additional property of light be exploited.

A new architecture is now proposed that we call the Multi-Wavelength Optical Content Addressable Parallel Processor (MW-OCAPP). It utilizes polarization-division multiplexing introduced in OCAPP combined with wavelength-division multiplexing to achieve an even higher degree of parallelism and system integration. The ability to propagate multiple-wavelength light-planes through the same space without mutual interference allows for true two-dimensional operations to take place. This enables the processing of multiple data arguments at the same time and within the same space, thus greatly increasing the parallelism of the processor over single-wavelength designs. Additionally, utilizing these additional degrees of freedom allows for a more compact system to be created, simplifying the manufacturing process and relaxing the alignment and power constraints.

2.0 Overview of the MW-OCAPP system architecture

Fig. 1 illustrates a structural organization of MW-OCAPP's processing model. The optical processing logic of MW-OCAPP consists of six modules: an optical Selection Unit, an optical Match-Compare Unit, an optical Equality Unit, an optical Magnitude Comparison Unit, an optical Relational Operations Unit, and an optical Output Unit. The MW-OCAPP architecture is designed in such a way as to implement a total of eleven database primitives. Most of these execute in a time-span that is independent of the problem size. MW-OCAPP can realize: difference, intersection, union, conditional selection, join, maximum, minimum, product, projection, division and update.

The inputs to MW-OCAPP are the comparand array (CA) and relational array (RA). Each row (tuple) of the CA is polarization logic encoded with different wavelengths by a multiwavelength source array and an electronically-addressable spatial light modulator. This form of encoding allows for the superposition and parallel processing of multiple comparands as they propagate through the Match-Compare and Equality units. The Selection Unit produces the Selection Register (SR), a light-plane that holds the multiple tuples in the Comparand Array to be matched. The optical Match-Compare Unit produces the Match-Compare Register (MCR), a wavelength/polarization encoded light plane that holds the locations of all the matched and mismatched bits. The Magnitude Comparison Unit takes the CA and RA and performs a magnitude comparison (greater-than and less-than) between CA and RA tuples, and outputs less-than (LR) and greater-than (GR) registers. The optical Equality Unit takes the MCR and produces an output called the Equality Register (ER) that represents the intersection locations of the CA and RA tuples. The ER, LR and GR light-planes pass through the optical Relational Operation Processing Unit where they are operated on to produce the Relational Operation Registers (RORs). Lastly, the ROR and MCR light-planes are routed through the optical Output Unit that interfaces with a host computer.

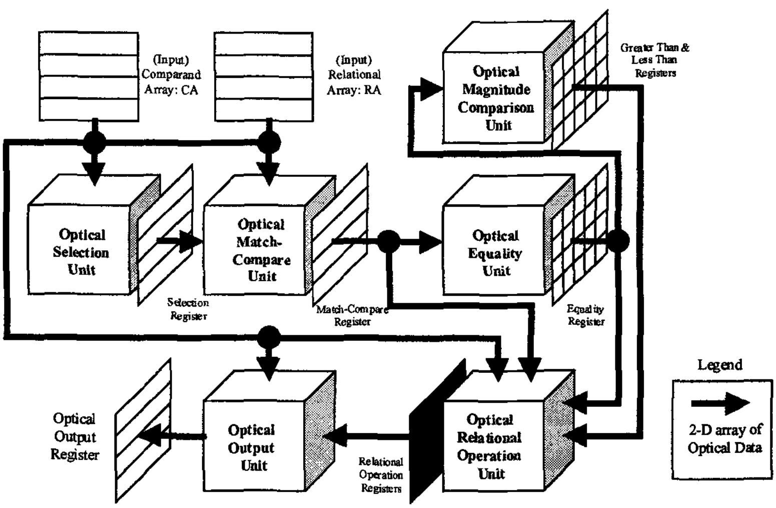


Fig. 1. MW-OCAPP Schematic Organization

3.0 MW-OCAPP Optical Implementation

3.1 Data Encoding

MW-OCAPP uses several methods for encoding a data-plane on a light-plane. Binary patterns are represented by spatially distributed orthogonally-polarized locations on a 2-D pixilated grid [11]. Logical '1' is defined as vertically polarized light and logical '0' as horizontally polarized light. The presence or absence of light (intensity threshold) within a light-plane indicates the selection or de-selection of tuples or attributes in the system. Individual tuples are differentiated from one another by polarization encoding each on a unique wavelength.

3.2 Implementation of Equivalence Operation

The equality operation is one of the most basic operations that a database machine must perform. The equality operation is rooted in the XOR concept:

$$[CA_{(m-1)}CA_{(m-2)}\ldots\ldots CA_{(1)}CA_{(0)}] \oplus [RA_{(m-1)}RA_{(m-2)}\ldots\ldots RA_{(1)}RA_{(0)}] = \{ [CA_{(m-1)} \oplus RA_{(m-1)}]\ [CA_{(m-2)} \oplus RA_{(m-2)}] \ldots\ldots [CA_{(1)} \oplus RA_{(1)}]\ [CA_{(0)} \oplus RA_{(0)}] \} \quad (1)$$

where 'm' represents the bit position in the words to be compared and the symbol '⊕' represents the logical XOR operation. The Comparand Array (CA) is the data array that resides in the comparand registers and Relational Array (RA) is the main database that occupies the main associative memory of the CAM. If a CA word and an RA word are a match, formula (1) will produce a resultant word containing only logical '0' bits:

if $CA_{(m-1)} = RA_{(m-1)}, CA_{(m-2)} = RA_{(m-2)}, \ldots CA_{(1)} = RA_{(1)}$ and $CA_{(0)} = RA_{(0)}$, then

$$[CA_{(m-1)}CA_{(m-2)}\ldots CA_{(1)}CA_{(0)}] \oplus [RA_{(m-1)}RA_{(m-2)}\ldots RA_{(1)}RA_{(0)}] = [\,\text{'0'}_{(m-1)}\ \text{'0'}_{(m-2)}\ldots \text{'0'}_{(1)}\ \text{'0'}_{(0)}\,] \quad (2)$$

If the CA and RA do not match, the resultant XOR word will be a mixture of '0' and '1' bits. Determining equivalency results from simply logical 'OR'ing all of the bits together in this intermediate word. The two words are mismatched if the result is a '1', and likewise the words are equivalent if the result is a '0'. The optical Equality Unit operates under these same basic principles, just in a much more parallel fashion.

Testing for equivalency with MW-OCAPP requires three optical units in the architecture. The units involved are the optical Selection Unit, optical Match-Compare Unit and optical Equality Unit. Fig. 2 shows the example input (Comparand Array and Relational Array) and the output Equality Register. In this example, the first three bits of the Comparand Array tuple "1100" are compared with the first three bits of each tuple in the Relational Array. Such a search is also known as a similarity search in that a subset of the comparand tuple is being compared with a subset of the relational array. The following descriptions of the three optical processing units are based on this example.

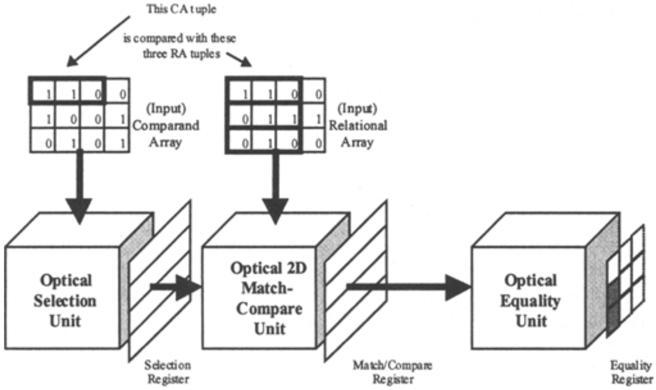


Fig. 2. Schematic organization for the Equivalency operation. The bold rectangles illustrate a similarity-search example (search for a match within a masked field).

3.2.1 Optical Selection Unit

The optical Selection Unit is illustrated in Fig. 3. Its purpose is to encode a pixilated two-dimensional optical wavefront with the comparand array (CA) to be processed. The "rows" in the wavefront, each encoded on a unique wavelength, represent tuples in the CA. Polarization encoding of the desired data pattern is employed to differentiate the binary states of each of the pixilated "bits".

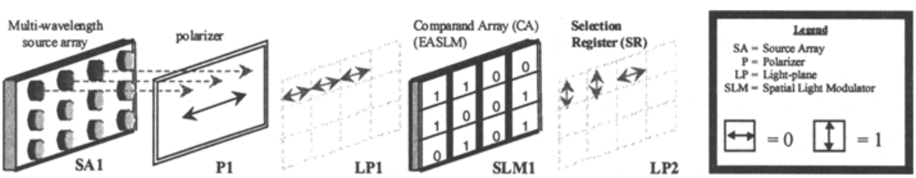


Fig. 3. Optical Selection Unit

The optical Selection Unit begins with a multi-wavelength source array (SA1) in which each row (which corresponds to a separate tuple) radiates at a different wavelength. Only a single wavelength is required, so only the first row is selected to radiate. Since only the first three bit positions in row one are involved in this operation, the source in the last column is de-selected. Therefore, SA1 indirectly functions like a masking register in the CAM. This wavefront passes through a horizontally-oriented polarizer (P1) to reset all of the bit positions to the '0' logical state (LP1). Light-plane LP1 impinges on an electronically-addressable spatial light modulator (SLM1) which polarization-encodes the light passing through it with the bit pattern 1-1-0. The resultant light-plane, LP2, is called the Selection Register (SR) and represents the optically-encoded version of the comparand array.

3.2.2 Optical Match-Compare Unit (MCU)

Fig. 4 illustrates the optical Match-Compare Unit. Its purpose is to bit-wise exclusive-or (XOR) each tuple in the comparand array (after being encoded in the Selection Unit and passed to the MCU as the SR) with each tuple in the relational array (RA). This produces a logical '1' at every bit position where there is a mismatch between the CA and RA.

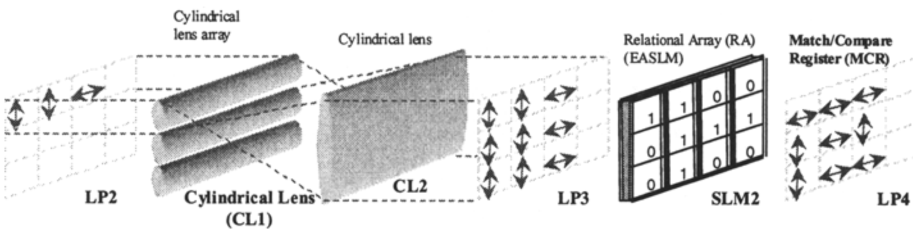


Fig. 4. Optical Match-Compare Unit

The encoded light plane from the optical Selection Unit (LP2) passes through a lens array which spreads each of the rows (LP3) with different wavelengths over the full surface of an EASLM (SLM2). Light plane LP3 passes through SLM2 encoded with the relational array (RA) to be searched. The EASLM rotates the polarization(s) of the incident light according to the logic states of its pixels, effectively generating the result of the logical XOR operation in LP4. Light plane LP4 is called the Match-Compare Register (MCR) and contains all of the bit match and mismatch locations of each of the CA and RA tuple combinations (designated by horizontally and vertically-polarized light respectively).

3.2.3 The Optical Equality Unit (EU)

The Equality Unit's purpose is to identify which combinations of CA and RA tuples are matches. It does so by operating on the Match-Compare Register and converting it to a pixelated map called the Equality Register that represents the equivalency of all of the CA and RA tuple combinations.

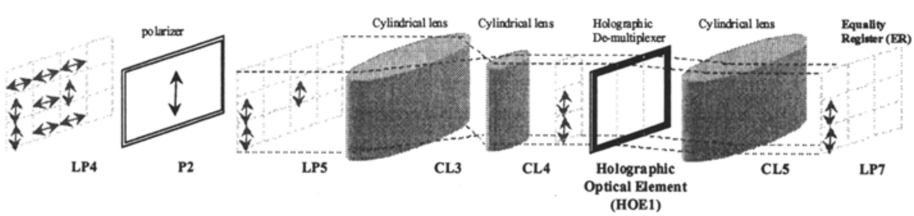


Fig. 5. Optical Equality Unit

Fig. 5 illustrates the optical Equality Unit. The MCR (LP4) enters the Equality Unit and passes through a vertically-oriented polarizer (P2) to form LP5. LP5 contains an illuminated pixel corresponding to all bit mismatch positions. LP5 is funneled down to a single column by CL3 and CL4. This single column (LP6) must now be wavelength de-multiplexed into a plane that has a pixel count width equal to the number of tuples in the CA. This can be accomplished using a holographic element (HOE1) that is fabricated to deflect light at an angle that is a function of its wavelength. Cylindrical lens (CL5) collimates the light exiting HOE1 and produces the Equality Register (LP7).

Decoding this Equality Register light-plane is fairly simple. The light-plane is a two-dimensional representation of the intersection of the CA and RA. If 'n' represents the number of tuples in the CA and 'm' represents the number of tuples in the RA, then the ER must consist of *m* X *n* pixels. It is encoded in "negative logic" meaning that non-illuminated pixels correspond to exact matches. For an *m* by *n* ER grid, $pixel_{mn}$ is illuminated such that tuple RA_m is not-equal-to tuple CA_n.

3.3 Magnitude Comparison Operation

Magnitude comparison is the second fundamental operation that MW-OCAPP implements. Operations of this type include the greater-than, less-than, in-bound, out-of-bound, and extremum tests. The magnitude comparison functional schematic organization is shown in Fig. 6. The input to the optical Magnitude Comparison Unit is the Equality Register from the Equality Unit, and the output is the Less-than (LR) and Greater-than (GR) registers [4]. The algorithm that MW-OCAPP uses to perform this operation can be broken down into four steps: (1) compute and store the Comparand Rank Comparison Register (CRCR) comparing the CA with a rank table; (2) compute and store the Relational Rank Comparison Register (RRCR) comparing the RA with a rank table; (3) compute and store the Equivalency Register (EQR) comparing the CA and RA; (4) compute and output the Less-than (LR) and Greater-than (GR) registers. Tasks 1-3 are processed by the optical Selection, Match-Compare and Equality units, and the results (the Equality Registers) are stored sequentially in the Optical Buffer Subunit. Step 4 of the algorithm requires that these three registers (termed the Equivalency Register (EQR), the Comparand Rank Comparison Register (CRCR), and the Relational Rank Comparison Register (RRCR)) be presented simultaneously to both the Rank Thresholding Subunit and the LR Extraction Subunit for final processing.

The Optical Buffer Subunit which performs the temporary storage of the EQR, CRCR and RRCR can be realized using an integrated "smart-pixel array" (SPA) [12]. The subunit consists of a single detector array matched to the dimensions of the Equality Register, and three polychromatic emitter arrays of the same dimensions. Hybrid source-detector modules can be realized using flip-chip bonding [13].

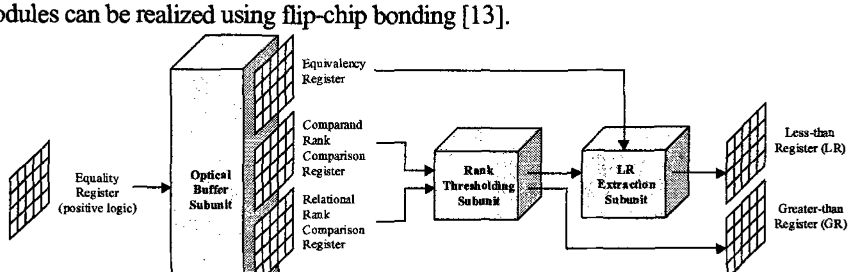


Fig. 6. Magnitude Comparison Functional Schematic Organization

In the following discussion, a single comparand bit pattern (1-1-0) is compared with a single relational bit pattern (1-1-1). Fig. 7 illustrates the Selection, Match-Compare and Equality Units in series that are configured to perform Step 1 in the magnitude comparison algorithm. The hardware processes the comparand word by testing it for equivalency against a ranked binary look-up table. The lookup table (SLM2) is an EASLM encoded with sequential binary words from 0 to $2^m - 1$ (one word per row) arranged in ascending order from top to bottom. The number of entries in the binary look-up table, 2^m, is determined by the maximum wordlength m that the unit is processing. This "equality" operation reduces the input word to a single pixel whose vertical position in the light-plane indicates its absolute magnitude. Light-plane LP7 is converted to positive-logic (swapping illuminated pixels for non-illuminated ones) using trivial hardware and is stored as the CRCR (LP8) in the Optical Buffer Subunit (Fig. 8a).

Step 2 in the magnitude comparison algorithm essentially is identical to Step 1 except that the Relational Array is loaded into SLM1 instead of the Comparand Array. Light-plane LP7 produced in this step in the algorithm is stored in its positive-logic form (LP9) as the RRCR in the Optical Buffer Subunit (Fig. 8b).

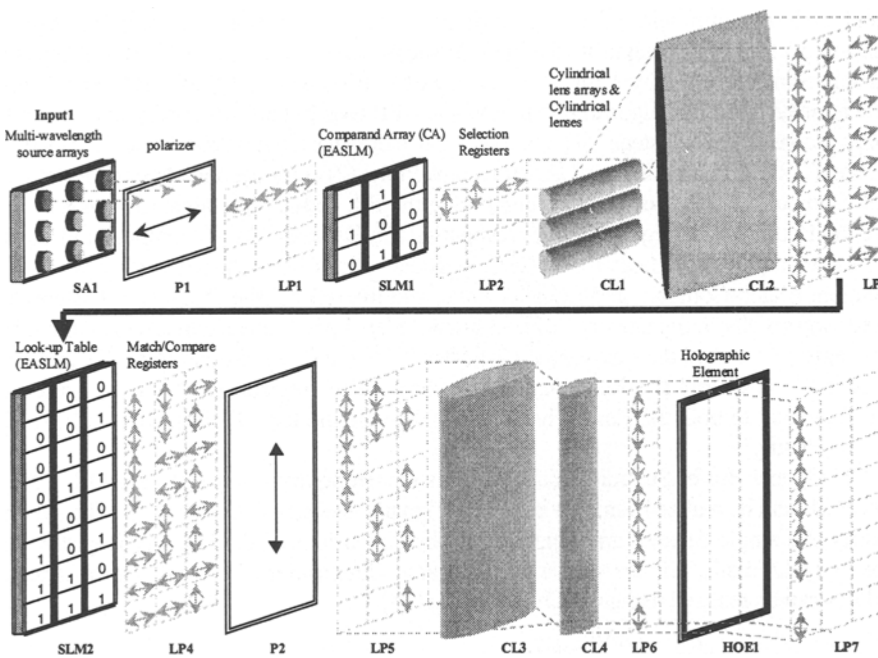


Fig. 7. Step 1 of the Magnitude Comparison Algorithm

Step 3 in the algorithm is most closely related to the equality process described in section 4.3 of this paper. The CA and RA are compared in the usual way and the resultant Equality Register is stored in its positive-logic form in the Optical Buffer Subunit as the EQR (Fig. 8c).

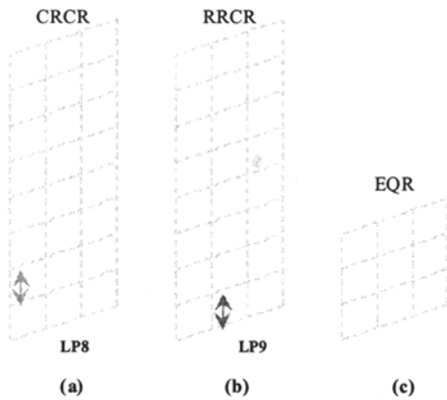


Fig. 8. (a) The Comparand Rank Comparison Register (CRCR); (b) The Relational Rank Comparison Register (RRCR); (c) The Equivalency Register (EQR)

Step 4 in the magnitude comparison algorithm directs the Optical Buffer Subunit to present the EQR, CRCR and RRCR registers simultaneously to the Rank Thresholding and LR Extraction Subunits for final processing[14]. This process is illustrated below.

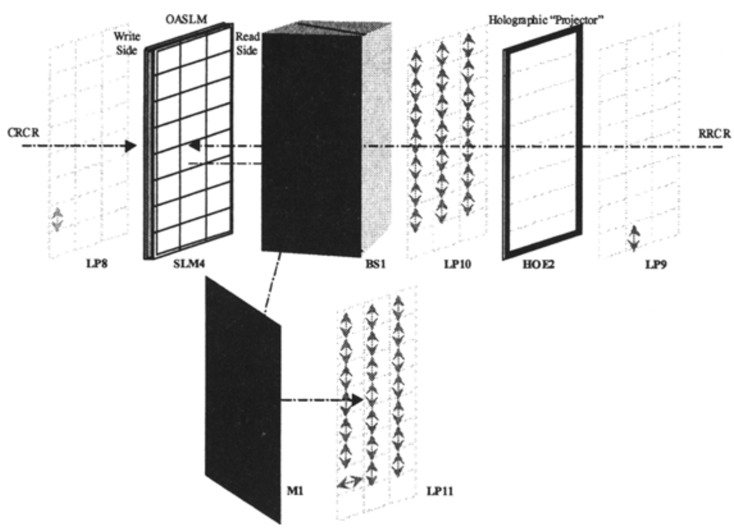


Fig. 9. The Rank Threshold Subunit (part 1)

Fig. 9 illustrates the first part of the Rank Thresholding Subunit (RTS). The RRCR (LP9) encounters a holographic "projector" element (HOE2) with a very specific fan-out function. A pixel in the ith row of the incident light-plane must be projected to every row r from $r = 1$ to $r = i - 1$. This function can most easily be realized by creating an array of discrete sub-holograms over the surface of the holographic plate. Each sub-hologram has a specific fan-out function (varying from top to bottom) and is tuned to a specific wavelength of interest (varying left to right). Relating this to the discussion, the illuminated pixel of LP9 occupies row eight. The fan-out function of the holographic element at this location produces a light-plane (LP10) in which rows one through seven are illuminated. Meanwhile, the CRCR light-plane (LP8) impinges on the write side of an OASLM (SLM4) which rotates the polarization states of LP10 that reflects off of its read-side. This light-plane (LP11) is steered out of the system by beamsplitter (BS1) and mirror (M1) combination. LP11 contains a horizontally-polarized light pixel for every CA/RA tuple pair such that the RA tuple exceeds the CA tuple in magnitude. In this example, it can be seen from the single horizontally-polarized pixel in LP11 that the RA tuple, 1-1-1, is greater than the CA tuple, 1-1-0. The pixel residing in the first column of LP11 indicates that it corresponds to the first comparand of the CA. The specific wavelength of this plane determines which tuple in the RA it corresponds to. In this case, there is only one RA tuple to be compared, so there can be only one wavelength. If a second CA tuple, 0-1-1, were also compared with the existing RA tuple, there would exist in LP11 a horizontally-polarized pixel in the 4th row of column two. Since RA tuples are differentiated by wavelength at this stage, adding additional RA tuples would translate into overlapping but independent light-planes coexisting in LP11. This light-plane must now be manipulated such that it can easily be sensed by a detector array at the output.

Fig. 10 illustrates the second part of the Rank Threshold Unit (RTU). The output (LP11) from Part 1 passes through a horizontally-oriented polarizer (P5) which allows only the modified pixels to pass. This light-plane (LP12) contains the relative magnitude comparison information between all of the tuples in the comparand array and all the tuples in the relational array. Further processing allows this information to be easily interpreted. The light-plane passes through a lens array (CL4 & CL5) that funnels the plane down to a single row. This row then passes through a holographic element such that the light is deflected vertically at a wavelength-dependent angle. LP14 is termed the Greater-than Register (GR) and contains an illuminated pixel for every CA/RA combination such that RA_m is greater in magnitude than CA_n. For an m by n GR grid, $pixel_{mn}$ is illuminated such that tuple RA_m is greater-than tuple CA_n.

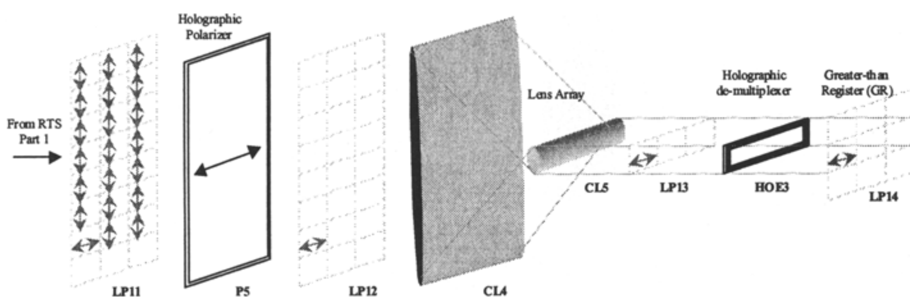


Fig. 10. The Rank Threshold Unit (part 2)

The magnitude comparison architecture has been used thus far to compare a single-comparand 1-1-0 with a single tuple in the relational array, 1-1-1, and produce the example GR. Using the same algorithm, it can be shown that the GR shown in Fig. 11(c) results from the RTU operating on the CA and RA in Fig. 11(a) and Fig. 11(b). Extracting the Less-than register from the GR requires logical bit-wise NOR'ing the GR with the positive-logic version of the Equality Register shown in Fig. 11(d). The resulting light-plane shown in Fig. 11(e) is the Less-than register (LR).

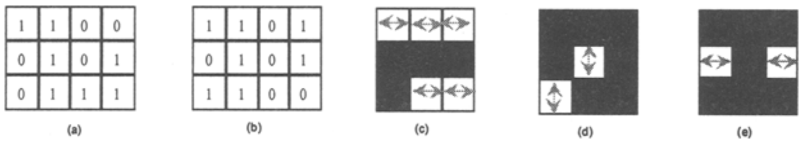


Fig. 11. Magnitude Comparison of the CA (a) and RA (b). Each row in the CA and RA is a separate tuple. The greater-than register (c) is generated by the Rank Thresholding subunit operating on (a) and (b). The LR Extraction subunit takes the logical NOR of (c) with the positive-logic version of the equality register (d) to produce the less-than register (e)

Fig. 12 illustrates the LR Extraction Subunit required to realize this NOR'ing process. Both the GR (LP8) and the ER (LP9) enter LR Extraction Subunit and are OR'ed together using beamsplitter BS1 to produce LP10. LP10 impinges on the write side of an OA-SLM (SLM3). At the same time, a horizonatally-polarized light-plane is launched from SA2. It reflects off of OA-SLM (SLM3) and has the polarization states of its pixels modified according to the illumination pattern on its read side. All pixels that had their polarization states rotated 90 degrees will be blocked by polarizer P4. Light-plane LP11 exiting the module is the logic-reversed version of LP10, otherwise known at the Less-than register (LR).

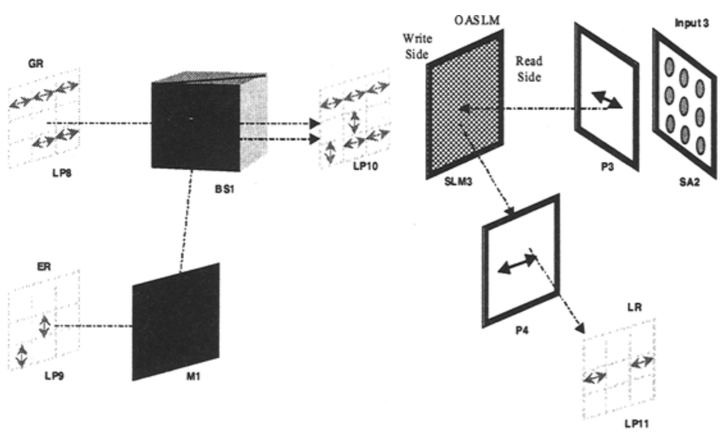


Fig. 12. LR Extraction subunit. Extraction of the less-than register (LR) using the equality register (ER) and the greater-than register (GR) as inputs.

Decoding of the LR is identical to that of the GR and ER. The plane's width in pixels is equal to the number of tuples in the comparand array and the height is equal to the number of tuples in the relational array. For the LR, an illuminated pixel indicates that a specific tuple in the relational array is less-than a specific tuple in the comparand array. For an m by n LR grid, $pixel_{mn}$ is illuminated such that tuple RA_m is less-than tuple CA_n.

3.4 Physical Demonstration of a Preliminary Version of MW-OCAPP

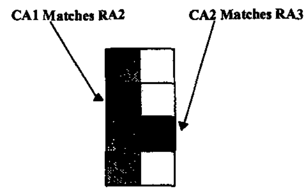
This section presents the physical demonstration of MW-OCAPP that has been done thus far. In this preliminary demonstration, the Equality Register that contains the "exact-match" information between each of the tuples in the RA and CA is generated. Fig. 13 shows the bit patterns contained in the example RA and CA as well as the expected Equality Register that results from the operation. The Comparand Array (CA) contains two tuples, "0-0-0-0" and "1-1-1-1". These are compared against four tuples in the Relational Array (RA).

CA1	0	0	0	0
CA2	1	1	1	1

(a)

RA1	1	0	0	1
RA2	0	0	0	0
RA3	1	1	1	1
RA4	1	1	0	0

(b)



(c)

Fig. 13. The experimental setup matches two tuples found in (a) the Comparand Array (CA) with the four tuples found in (b) the Relational Array (RA). The Equality Register that results (c) indicates that there is a match between CA1 and RA2 as well as CA2 and RA3. Non-illuminated (black) pixels indicate an exact match.

The experimental setup required to implement this is displayed in Fig. 14. The vertically-polarized source radiation comes from a 2W argon ion laser in its multi-line configuration. This beam passes through an afocal beam expander lens system that broadens the beam to a 1.5cm width. This multi-line beam is now filtered to extract the 488.0 nm (blue) and 514.5 nm (green) spectral lines. One of these beams has its polarization rotated by placing a quarter waveplate in its path. This "color" will hold the results from CA2 and the other will hold the results from CA1. These two purified beams are recombined using a cube beamsplitter and impinge off of a FLC spatial light modulator. This SLM is a reflection-mode device that rotates the polarization states by 90 degrees of each of the addressed pixels. It is encoded with the four tuples contained in the relational array. This passes through a vertically-oriented polarizer and some imaging lenses that focus the plane down to a single column on the screen. A holographic grating is placed between the lens system and the screen in order to spatially separate the two color channels into individual columns.

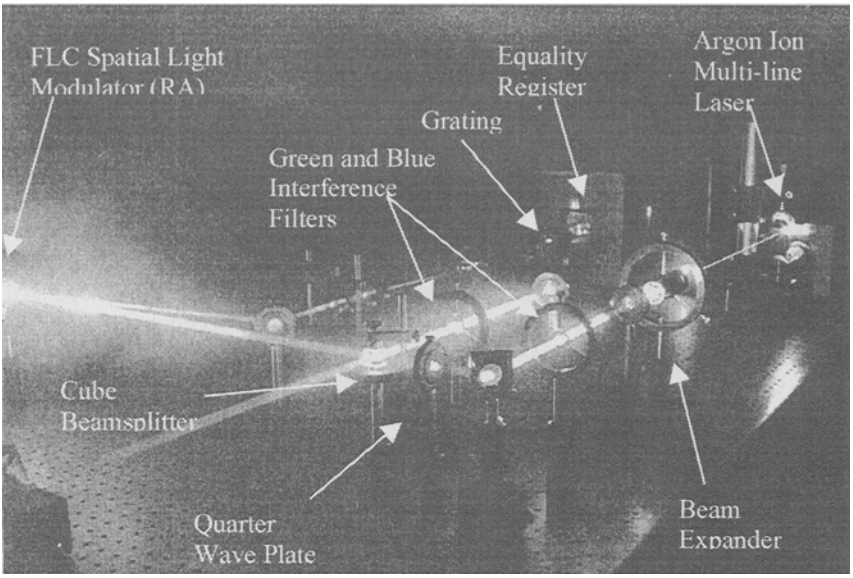
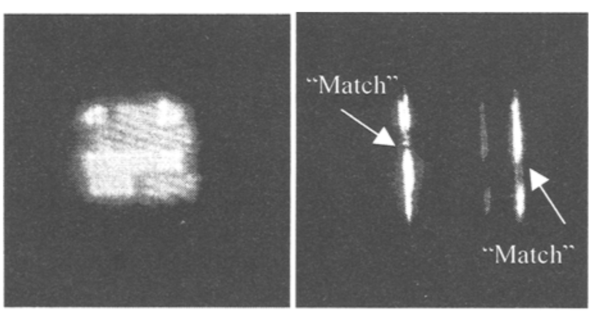


Fig. 14. Demonstration system photograph

Fig. 15 shows the Equality Register at several points in the imaging system. Fig. 15a is an image of the light plane just prior to its passage through the imaging optics. Both the green and blue channels completely overlap. Fig. 15b shows the Equality Register at the focal plane. Notice that there is a dark pixel in the second row of the first column and in the third row of the second column. Both of these locations correspond correctly to tuple "matches" predicted in Fig. 13.



(a) (b)

Fig. 15. The Equality Register at (a) just prior to wavelength demultiplexing, and (b) at best focus. The blurring is caused by the low shutter speed required to image the registers combined with the page-swap refreshing of the FLC SLM

4 Discussion/Conclusions

In this paper, an optical associative processing system called MW-OCAPP is presented. It harnesses a unique method of wavelength and polarization-multiplexing of dataplanes to achieve a high level of parallelism. Optical implementation is made possible by exploiting the non-interactive behavior of coincident light-planes of differing wavelength. This architecture offers database systems constant-time parallel equality and magnitude comparison of multiple comparands with multiple tuples in a relational array.

When compared with conventional iterative word-parallel magnitude comparison schemes where w is the wordlength and n is the number of comparands to be operated on, MW-OCAPP's magnitude comparison algorithm offers a speedup of wn. This performance suggests a substantial performance improvement over previous designs in database operations such as sorting which typically use the magnitude comparison operation repetitively. Additionally, MW-OCAPP's multi-comparand approach offers a speedup of m over conventional word-parallel CAM-based systems, where m is the number of comparands to be compared and n is the number of tuples in the database.

This research was supported by National Science Foundation grant MIP-9505872.

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