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Opto-Electronic Integrated Information System

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SUMMARY As a new category of the optical application system integrated with electronics, the opto-electronic information system (OEIS) is presented. Combination of the different characteristic technologies, optics and electronics, is expected to be useful for development of an effective and high-performance information systems. The properties of the optical technologies such as parallelism, high-speed, and large information capacity can be utilized for information processing. Even if some of the functions are emulated by the electronics, the optics give more effective solutions. To implement the OEIS, various optoelectronic devices and fabrication technologies are available including vertical cavity surface emitting lasers and spatial light modulators. There are two forms of system construction for the OEIS: an application of optics to an electronic-based system and the reversed form. As examples of the OEIS, the parallel matching architecture (PMA) and the thin observation module by bound optics (TOMBO) are presented. The PMA is an architecture of parallel computing system specified for global processing. This architecture shows a typical strategy to utilize the optical interconnection capability with flexibility of the electronic technology. The TOMBO presents possibility of morphological conversion using combination of the optical and electronic technologies. A compound-eye imaging system and post digital processing enable us to realize a very thin image capturing system. The issues related on development of the OEIS are proper usage of optics, effective fusion of the optical and electronic technologies, methodologies for system construction, fabrication supporting tools, and development of attractive demonstrators other than communication and interconnection fields.

key words: *optical interconnection, optical processing, smart pixels, optoelectronics, information system*

1. Introduction

According to the development of electronics and optoelectronics, a variety of information systems have been designed and constructed. Although semiconductor integration is nothing but the foundation of these systems, optical technologies also serve important functions in the systems. The optical technologies provide various excellent features, e.g., parallelism, high-speed, large information capacity, and so on. Using the features combined with the current electronic technologies, we can achieve efficient and high-performance information processing.

Optical interconnection is a good example of the optical application in electronics systems [1]. Connection capability of the light is expected to solve the inherent problems associated with high density integration of semiconductor devices. As the integration density increases, signal propagation latency by the interconnection line becomes dominant in the processing time. On the other hand, light propagation in free-space is free from the restriction. Therefore, optical interconnection is recognized as an important solution for future system integration. Up to date, a variety of test-beds and demonstrators have been presented as well as theoretical studies on the issue [1]–[5].

In spite of the emerging features of the optical interconnection, application targets of the optical technologies can not be restricted to that specific problem. A lot of efforts have been devoted to the application of optics in information processing. The research field is categorized as optical information processing or optical computing. A typical instance of the application is optical Fourier transform by a convex lens and many interesting ideas for information processing are accumulated and ready to use [6]. Considering the situation, sophisticated application of the optics combined with the state-of-the-art electronics provides a promising form of information system.

In this paper, a new category of optical application system called opto-electronic information system (OEIS) is presented. After brief description of the system, two kinds of experimental systems under developing by the authors' group are explained. In Sect. 2, the features and advantages of the OEIS are described. In Sect. 3, possible forms of the OEIS are shown. In Sect. 4, example systems of the OEIS are introduced as the instances of the proposed concept. Finally, the future issues related on the development of the OEIS are summarized.

2. Opto-Electronic Information Systems

The OEIS is defined as a framework of information processing system based on fusion of the optical and electronic technologies. As is well known, the electronics is advantageous in precision, flexibility, integration,

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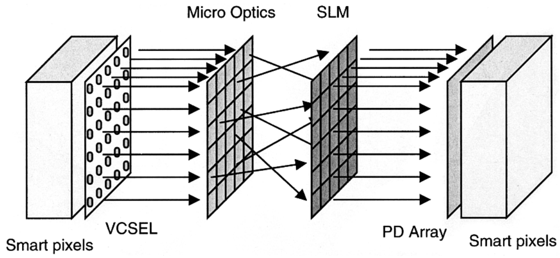


Fig. 1 Free-space optical interconnection system.

and packaging, whereas the optics has features in parallelism, high speed, large bandwidth, noise resistance, and visibility. Therefore, combination of the different characteristic technologies is expected to be useful for development of an effective and high-performance information processing system.

The properties of the optical technologies useful for information processing are mentioned as follows: parallelism, high-speed, self-coherence, mutual-incoherence, large information capacity, multi-dimensionality, signal continuation, large fan-in and fan-out, visibility, remote manipulation, nonlinearity, and so on. These properties come from the physical characteristics of light. Even if some of the functions are emulated by the electronics, the optics gives more reasonable solutions with respect to processing efficiency.

As a reference, a typical form of free-space optical interconnection system is shown in Fig. 1. The system is composed of various devices and technologies in optoelectronics as well as electronics. This free-space optical interconnection system is considered as a primitive form of the OEIS, so that the devices and technologies in the system can be utilized for development of the OEIS. Semiconductor integrated circuits are indispensable for high density packaging of processing functions. Customized complementary metal-oxide semiconductor (CMOS) integrated circuits [7] and field programmable gate arrays (FPGA's) are available for the purpose. As optoelectronic devices, vertical cavity surface emitting lasers (VCSEL's) [8], a variety of spatial light modulators (SLM's) [9], and integrated photo-detectors are developed. A composite device consisting of the semiconductor integrated circuits and the optoelectronic devices is called smart-pixel, which plays an important role in the OEIS's [10]. To tame the light propagation, fabrication technology on micro optical elements based on the lithography is mature [11]. As promising technologies, photonic crystals [12] and micro optoelectronic mechanical systems (MOEMS's) [13] are expected to be applicable.

3. Forms of System Construction

There are two forms of system construction for the OEIS as shown in Fig. 2. The first is that the optical technology is applied to an electronic system to improve specific functions. This is a conventional form of the optical application system. The second is a form in which the optical proper functions are substituted by the electronic technology. This form seems unreasonable especially for researchers in the optical community. However, if flexibility and integration capability of the electronics are considered, it is a quite effective method for system construction.

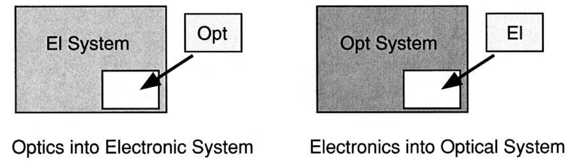


Fig. 2 Forms of OIES construction.

3.1 Application of Optics to Electronic System

Application of the optical technology to an electronic system enhances communication capability of the system. Based on broad bandwidth provided by high frequency and parallelism of the light wave, an optical backplane for a multiprocessor system [3] and an interchip interconnection [4] are proposed. Free-space configuration enables us to rearrange the spatial order of light signals, which is applied to an interconnection network system [5]. In addition, the physical property of light accelerates specific functions. Global processing over multiple data [14] and ultra-fast space-to-time and time-to-space signal conversions [15] are good examples.

3.2 Application of Electronics to Optical System

Examples of the systems in which the electronic technology substitutes the optical function are frequently found in commercial products. Digital cameras and movie recorders are typical systems in which semiconductor devices take the place of photographic films. Moreover, the electronics provides an effective method to simplify the bulky optical systems. For example, discrete correlation, which has been recognized as one of the most effective operations by optical processing, can be flexible in operation and simplified on hardware if we introduce the electronic technology to it [16]. As an interesting idea, morphological conversion of the system hardware can be achieved by the composition as shown in the next section [17].

4. Example Systems

In this section two experimental systems under developing by the authors' group are presented. Due to variation in the implementation of the OEIS, introduction of the emerging system will be helpful to understand the concept. The parallel matching architecture (PMA) is

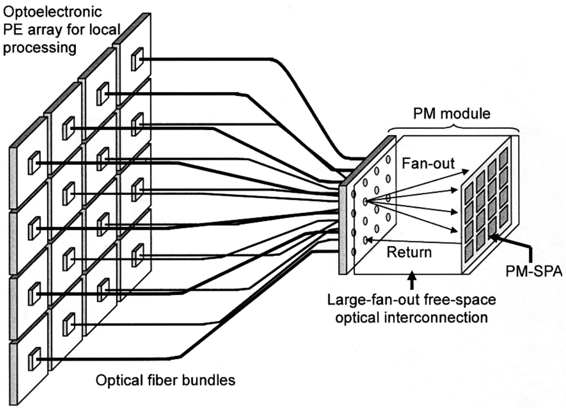


Fig. 3 Parallel matching architecture.

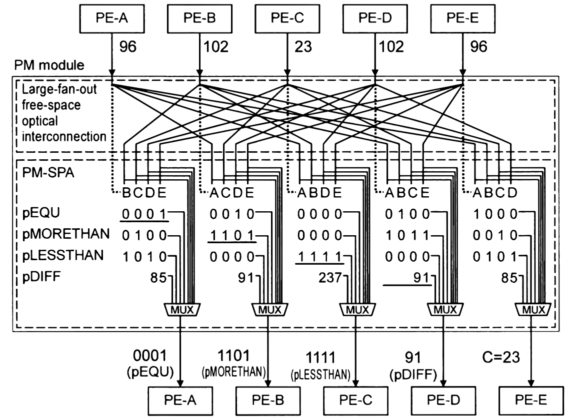


Fig. 4 Data flow around PM module for 5 PE's case.

Table 1 Matching operations for PMA.

Operation	Operands	Return	Expression
EQU	d_i, d_j	b_i	Is d_i equal to d_j?
MORETHAN	d_i, d_j	b_i	Is d_i more than d_j?
LESSTHAN	d_i, d_j	b_i	Is d_i less than d_j?
DIFF	d_i, d_j	n_i	$d_j - d_i$.

d: data from PE. b: binary value. n: numerical value.
Suffix is identifier of source or destination PE.

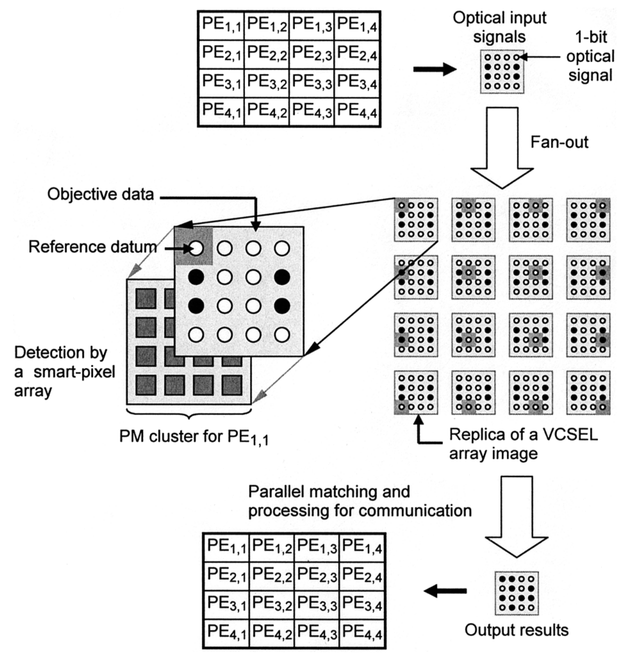


Fig. 5 Optical interconnection in PMA.

an example of the first form and the thin observation module by bound optics (TOMBO) is that of the second form of the OEIS.

4.1 Parallel Matching Architecture (PMA)

The PMA is a framework of parallel computing system that provides powerful processing capabilities for global processing [14]. The PMA is composed of a global processor called parallel-matching (PM) module and multiple processing elements (PE's). The PM module is implemented by free-space optical interconnection with large fan-out and a PM smart-pixel array. Figure 3 shows a schematic diagram of the PMA. Although optical fiber bundles are adopted to communicate between the PE's and the PM module, this implementation is alterable.

The PMA aims to accelerate global operations commonly appeared in distributed optimization algorithms such as the genetic algorithm [18]. A global operation is defined as an operation that treats multiple data over the PE's. In a distributed optimization algorithm, each PE evaluates score of the cost function and the host processor compares the scores from the PE's to find a better solution. As you can imagine easily, the communication bandwidth becomes critical on the host processor, which restricts the processing capability of the system. To overcome this problem, the PMA employes the PM module dedicating to a set of global operations and large fan-out optical interconnection.

As primitives of the global operations, four kinds of matching operations are defined as shown in Table 1. These operations are applied to any combination of the data pair over the whole PE's. The collective operations for all PE's are called parallel matching operation and executed in parallel on the PM module. For individual matching operations, four kinds of parallel matching operations, pEQU, pMORETHAN, pLESSTHAN, and pDIFF, are defined. Figure 4 shows an example data flow around the PM module for five PE's. As shown in the figure, the PM module also redirects the input data to another PE, which provides inter-PE data transfer capability.

Various interconnection topologies can be applied to the PMA. To utilize the interconnection capability of the optics, large fan-out interconnection is adopted in the PMA. Figure 5 indicates how to deliver the data of the PE's to the processing elements on the PM module (called PM clusters). The optical interconnection itself functions as an image duplicator of the optical signals

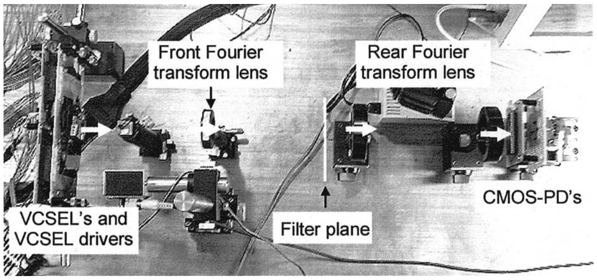


Fig. 6 Experimental setup for PMA.

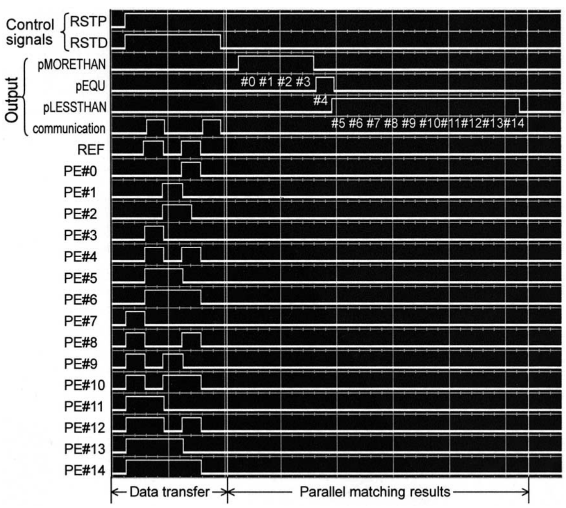


Fig. 7 Experimental result by PMA test-bed.

emitted from the PE's. Each PM cluster receives one of the duplicated images and executes parallel matching operations. Note that the individual PM cluster interprets the received image differently; the position of the reference data (i.e., d_i in Table 1) is changed according to that of the PM cluster. The return path from the PM clusters to the PE's is a set of one-to-one interconnections.

As an experimental test-bed of the PMA, an opto-electronic system around one PM cluster is constructed. Figure 6 shows the experimental setup. We assume 4×4 PE's arranged in a square array. The output signals from the PE's are emulated by 4×4 elements on a VCSEL array (Micro Optical Devices, Model Gigalase, 850 nm). For the optical interconnection, a computer generated holographic (CGH) is prepared. The CGH filter is composed of 2048×2048 pixels of $8.5\,\mu\text{m} \times 8.5\,\mu\text{m}$ area with two phase levels. The filter is designed by an iteration method based on the Gerchberg-Saxton algorithm [19] and fabricated with the electron beam lithography. The PM cluster is implemented by the 4×4 CMOS photo-detectors (Model N73CGD, U.S.-Japan Optoelectronic Project) and a complex programmable logic device (CPLD) (Cypress, Model FLASH374i).

Figure 7 is the experimental results of the PM operations and inter-PE communication running at 15 MHz. In this case, incremental values from one to fifteen are assigned to the output data of the PE#0–#14, respectively. The reference data is set as 5. Then the output signals of the PM cluster is monitored. As seen from the waveforms, the correct output is obtained. The total bit rate of the experimental test-bed was 240 Mbps. The speed is limited by the response time of the CMOS photo-detectors. If the smart-pixel technology is employed to the implementation, much better performance is expected.

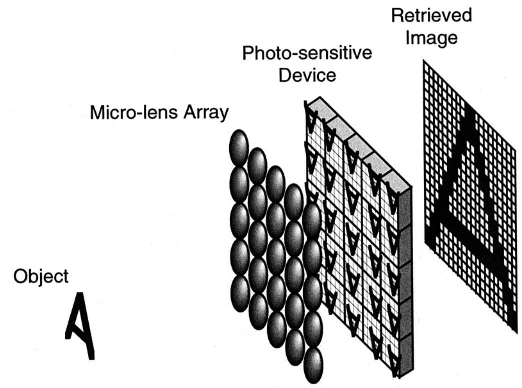


Fig. 8 Thin observation module by bound optics.

4.2 Thin Observation Module by Bound Optics (TOMBO)

The TOMBO is an optoelectronic image capturing system using a compound-eye imaging optics [17]. Figure 8 shows a schematic diagram of the TOMBO architecture. An important feature of the TOMBO is that the compound-eye imaging system is utilized to reduce the volume of the optics. After detecting the optical signals captured by the multiple lenses, the image of the object is retrieved from the signals. Although the image quality is inferior to that by the conventional imaging system, very thin system configuration is an attractive feature of the TOMBO architecture. This system is an interesting instance of morphological conversion using opto-electronic hybrid composition.

The compound imaging system can greatly reduce the working distance between the lens and the imaging plane. This distance is called back-focal length and changes according to the shape and the material of the lens. Due to limited variation of the possible shape design and the lens material, a typical back-focal length of a lens is roughly larger than the lens aperture. Therefore, reducing the aperture, this is the case of micro-lens, is reasonable to reduce the working distance. In addition, use of multiple lenses is effective to capture many light flux, which is a problem in small aperture lenses. As a result, an imaging system with thin and bright configuration can be implemented by the compound imaging optics.

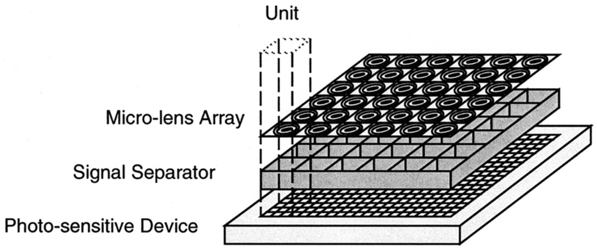


Fig. 9 Construction form of TOMBO.

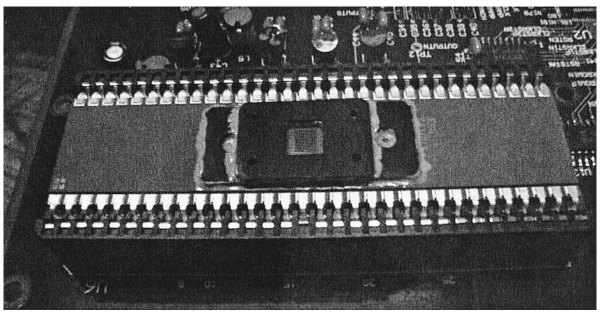
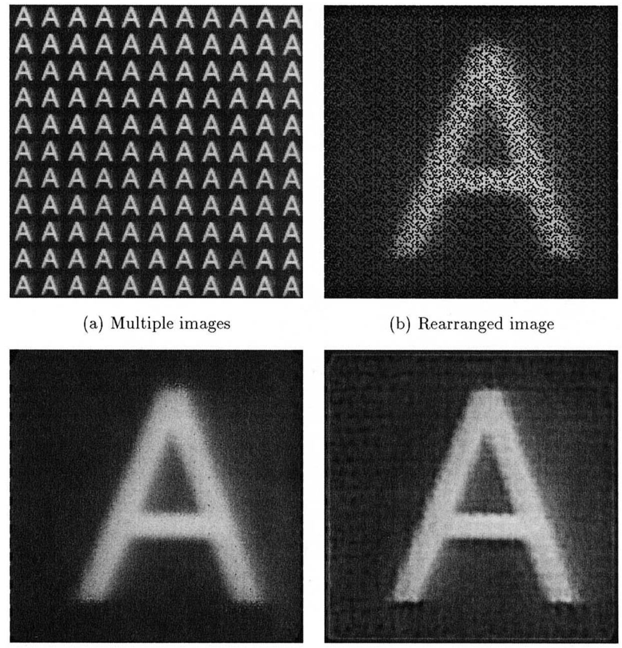


Fig. 10 Picture of TOMBO experimental system.



(a) Multiple images (b) Rearranged image

(c) Interpolated image (d) Edge enhanced image

Fig. 11 Captured image by TOMBO experimental system.

Figure 9 illustrates a typical construction of the TOMBO system. The system is composed of an array of micro-lenses, a signal separator, and a 2-D photo-sensitive device. These components are stacked to be a compact imaging device. Note that this device does not require any additional optical devices to capture an image. Packaging technologies in semiconductor integration, micro-optics, and micro-mechanics can be utilized to fabricate the system.

To demonstrate the TOMBO architecture, an experimental system is constructed using a custom CMOS image sensor. The CMOS image sensor has 320×240 pixels arranged with $12.5\,\mu$m intervals, which is fabricated by $0.6\,\mu$m CMOS process. The fill factor of each pixel is about 30%. Each micro-lens has $650\,\mu$m focal length and $250\,\mu$m diameter. The optical signal through the micro-lens, i.e., a small image, is captured by 20×20 elements on the CMOS image sensor. This elemental imaging system is called unit and the whole TOMBO system comprises 16×12 units. To avoid the cross talk between the adjacent units, the signal separator is inserted between the micro-lens array and the CMOS image sensor. As the signal separator for the experimental system, a stainless steal plate of $250\,\mu$m thickness is processed by a YAG laser. The maximum thickness of the wall is about $30\,\mu$m. Figure 10 shows a picture of the experimental system. Note that the micro-lenses and the signal separator are attached on the top of the CMOS package.

The captured image is retrieved after processing on the signals detected by the CMOS image sensor. The signals have a form of multiple small images corresponding to the individual units. Several retrieve algorithms have been considered for the processing. Among them, the pixel rearrange method shows a superior performance. In the method, the pixels on the units are rearranged on a virtual object plane according to the geometrical relation of the optical system. As the key points of the method, the pixel on the virtual object plane is not augmented and an linear interpolation is applied to fill the gaps between the rearranged pixels. These procedure serves as improving the effective resolution.

Figure 11 is an observed image by the experimental TOMBO system; (a) is the captured signal by the CMOS image sensor, (b) is the rearranged image, and (c) is the result of linear interpolation. In this case, correlation between the unit images are utilized to determine the offset value of each unit required for the rearrangement. To improve the image quality, median filtering and edge enhancement are effective as shown in Fig. 11(d). As seen from the final image, a good result is obtained. Note that this image is captured by a thin optical system not more than 4 mm. With appropriate packaging technologies in semiconductor fabrication, a very compact image capturing camera can be realized using the TOMBO architecture.

5. Future Issues

There exist a lot of issues to firm the foundation of the OEIS. We summarize some of them to clarify the problems for future development.

First, we must explore the proper forms of optical usage in the OEIS. Sophisticated adaptation of optics is a crucial issue for this specific system. For example, how to divide tasks for the optical and electronic subsystems is an interesting problem. Secondly, an effective method to fuse the two different characteristic technologies must be found. Gaps in the processing speed, the form of information, the available tools of the both technologies should be compensated. We also need an effective methodology for system construction including system design, simulation, performance estimation, and so on. Fabrication holds an important key for practical implementation of the designed system. System components, packaging techniques, and supporting software are typical subjects. Finally, development of a variety of demonstrators of the OEIS is a crucial issue. We are requested attractive demonstration other than communication and interconnection to show this fascinating system concept.

6. Conclusion

In this paper, the opto-electronic information system is presented as a new category of optical application systems integrated with the electronics. The parallel matching architecture and the thin observation module by bound optics show the potential capabilities of the proposed information systems. Combination of the optical technologies with the semiconductor integration technology is expected to be a promising form of system construction in near future.

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