Guided-wave multiwavelength polarization-insensitive processing module for a parallel multicomparand perfect-match algorithm

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We present a design for a planar guided-wave polarization-insensitive (intensity-based) optoelectronics module that provides a parallel perfect-match search for database and text processing. The module is based on a content-addressable memory model for parallel information retrieval. We propose the use of planar guided-wave optics with multiwavelength processing to achieve a substantially high degree of performance and parallelism. Based on initial performance analysis, the proposed module is capable of achieving an aggregate processing speed of 10^{12} bits/s. © 2000 Optical Society of America

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Any application requiring fast searches of databases, lists, or lookup tables can be extensively improved by use of content-addressable memory (CAM). CAM provides faster performance than random-access memory by comparing the desired information against the entire data simultaneously.[1] In an effort to increase the number of comparands (search words) that can be simultaneously compared against an array of database words in the traditional optical CAM (single-comparand),[2,3] we have developed an architecture called the multiwavelength optical content-addressable parallel processor (MW-OCAPP).[4] The MW-OCAPP uses a new technique called multiwavelength processing, which is similar in concept to wavelength-division multiplexing. As a result, the processing throughput of MW-OCAPP is significantly increased. However, MW-OCAPP faces a few drawbacks, owing to free-space bulk optics implementation. These include (1) slow switching speeds of free-space optics active devices, (2) diffraction-limit penalties with relatively long path lengths, (3) severe power losses owing to the fact that there are many components cascaded in a path, (4) misalignment and vibration problems, and (5) difficulties in adapting the workbench design to a compact system suited for the real-world environment. These difficulties prompted us to investigate other implementation techniques of optics, one of which is guided-wave technology.

In an attempt to eliminate the above-described problems, we have designed another architecture, based on guided-wave photonic technology. This new architecture is called an equivalency-processing parallel photonic integrated circuit ($\mathrm{EP^3IC}$).[5] The $\mathrm{EP^3IC}$ provides a quantum leap improvement in performance and reduction in size. The $\mathrm{EP^3IC}$ combines two major concepts: guided-wave optics and multiwavelength processing. Guided-wave optics offers the necessary switching speed for the active elements, and multiwavelength processing significantly increases the degree of parallelism. Although the $\mathrm{EP^3IC}$ is a powerful architecture in design, it too faces several limitations, especially in terms of implementation and realization. These include the use of orthogonal polarization to process information, which is currently hard to control, the lack of materials for two critical components that are required for the $\mathrm{EP^3IC}$ (the active polarization converter and the polarization filter are still in the research state), and significant power losses.

Hence the purpose of this Letter is to present a new module that overcomes these realization issues. We call this proposed module the multiwavelength equality search intensity-based (polarization-insensitive) guided-wave unit (MESIGU). Instead of using polarization as an encoding scheme to process information, the MESIGU uses intensity-based dual-rail logic. Consequently, in the MESIGU various design constraints (e.g., polarization integrity, the choice of wavelengths, waveguides dimensions) are relaxed, the hardware used in the $\mathrm{EP^3IC}$ (without any polarization filter) is simplified, and the design is more power efficient. Furthermore, the MESIGU can be realized with a wide range of existing intensity-based guided-wave components and techniques that are well developed from wavelength-division multiplexing technology (phase, intensity, polarization insensitivity, and electroabsorption). Therefore the MESIGU is much more realizable than is the $\mathrm{EP^3IC}$. Although the planar guided-wave optics in the MESIGU seems to have lost the multidimensional spatial parallelism and interconnection flexibility provided by free-space optics, the high degree of parallelism of the equality operation has been completely retained, since the MESIGU is algorithmically mapped from the MW-OCAPP. In addition, the overall throughput of the MESIGU will potentially be much higher than that of the MW-OCAPP (with free-space multidimensional parallelism), owing to the superior modulation speed provided by guided-wave components.

The equality search is one of the most basic operations for database processing. This search is basically a matching process based on exclusive–OR (XOR) operation. If two comparing words are a match, the XOR operation will produce a resultant word containing only logical 0 bits. If two words do not match, the resultant XOR word will be a mixture of 0 and 1 bits. Equivalency results can be determined by simply logical OR-ing all of the individual bits 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. Therefore the MESIGU requires two inputs and produces an output. The inputs are a comparand array (CA), representing the search words, and a relation array (RA), representing the database words. The output is the equality register, which is the result of the comparison between the CA and the RA.

The MESIGU uses dual-rail logic to encode binary logic on an optical signal.[2] Two pixels are required for representation of a binary state. Figure 1 illustrates the schemes of dual-rail logic. Logical 0 is encoded by two pixels as an opaque pixel on the left, followed by a transmissive pixel on the right in the CA, whereas logical 1 in the CA is represented by a transmissive pixel on the left, then an opaque pixel on the right. However, the RA data are encoded in the exact complement of the CA. Individual words on the CA are differentiated from one another by encoding each with a unique wavelength. In Fig. 1(b), the gray-level pixels represented by dashed boxes symbolize illuminated optical signals with a designated wavelength. The white pixels with dashed boxes, on the other hand, depict nonilluminated optical signals. In the CA and the RA, which is in effect a spatial light modulator, white pixels (with solid borders) represent the transparent state (in which all light is passed) and cropped-out pixels denote an opaque state (in which any light is blocked).

There are five types of component required in the MESIGU. As shown in Fig. 2, the key building blocks include the laser array, modulators for the CA, multiplexers, modulators for the RA, and demultiplexers and detectors. If there are m words in the CA, q words in the RA, and n bits in both the CA and the RA, then there must be 2^*m^*n sources with m wavelengths, 2^*m^*n CA modulators, 2^*n sets of multiplexers, 2^*q^*n RA modulators, q demultiplexers, and $m*q$ detectors. Since each bit is composed of a left and a right pixel, the MESIGU is designed to group all the left (or right) pixels of an arbitrary-order bit (e.g., the second bit) of all CA words (from CA$_0$ to CA$_m$) into proximity. The multiplexers perform a fan-out function of the combined wavelengths from the CA to the RA modulators. Subsequently, the branch of the same RA word from each group (regardless of left and right) will be channeled to the same demultiplexer, performing the logical OR-ing process. The demultiplexers then separate the wavelengths into the appropriate detectors. In the detector array the equality result is based on negative logic. Equality register ER$_{xy}$ is not illuminated when a CA word in order x is equal to a RA word in order y, where $x < m$ and $y < q$. Depending on the design, one can optionally combine the CA array with the directly modulated lasers to simplify the hardware used.

Figure 3 depicts the guided-wave implementation layout of the MESIGU, based on the model of Fig. 2. The unit is designed with four CA words, four RA words, and 2 bits. The four CA words in Fig. 3 are CA$_0$ = 00, CA$_1$ = 01, CA$_2$ = 10, and CA$_3$ = 11, whereas the four RA words contain RA$_0$ = 01, RA$_1$ = 11, RA$_2$ = 00, and RA$_3$ = 10. In Fig. 3, modulator CA2 of B1 left (transparent) and modulator CA2 of B1 right (opaque) in Fig. 3 make up the logical 1 of CA$_2$. The remaining logical 0 of CA$_2$ is made of modulator CA2 of B0 left (opaque) and modulator CA2 of B0 right (transparent). Note that the encoding of pixels for the RA data is the opposite of that for the CA, as depicted in Fig. 1. RA3 of B0 left (opaque) and RA3 in B0 right (transparent) of Fig. 3 make up the 1 of RA$_3$. The 0 is encoded into RA3 of B1 left (transparent) and RA3 of B1 right (opaque). The λ's in Fig. 3 indicate the presence of the wavelengths in the particular branches of the waveguides. The CA or RA modulators with $\times$'s are in fact opaque pixels that block all wavelengths. When they exit the waveguides, the wavelengths are demultiplexed by Rowland circle grating demultiplexer[6] and channeled into corresponding photodetectors. Each group (Q0–Q3) of photodetectors in Fig. 3 corresponds to detectors associated with a demultiplexing (Dx) group (Dx 1 to Dx q) in Fig. 2. For example, in group Q3 of Fig. 3, photodetector 2 is not illuminated. This corresponds to a nonilluminated pixel in ER$_{23}$, which means that there is a match between CA$_2$ and RA$_3$. A similar interpretation is applied to nonilluminated photodetectors E$_{02}$, E$_{31}$, and E$_{10}$.

A preliminary performance analysis of the proposed system with four CA words and two RA words of 2 bits each, running at a modulation speed of 9.7 GHz

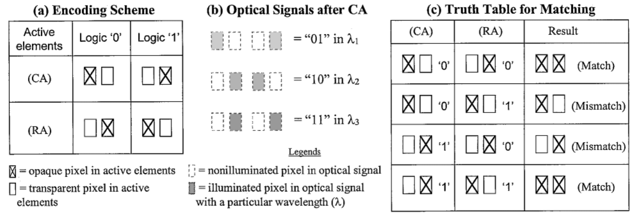

Fig. 1. Scheme of the dual-rail logic. λ, wavelength.

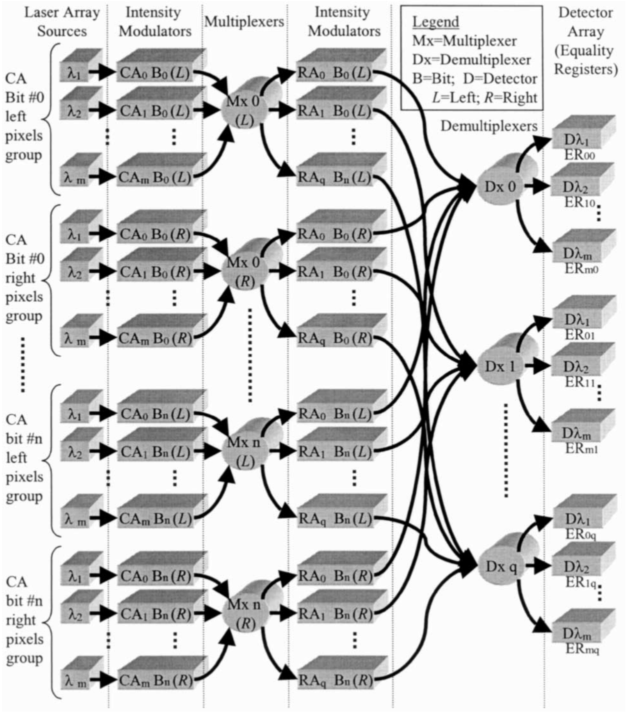

Fig. 2. Basic building blocks of the MESIGU.

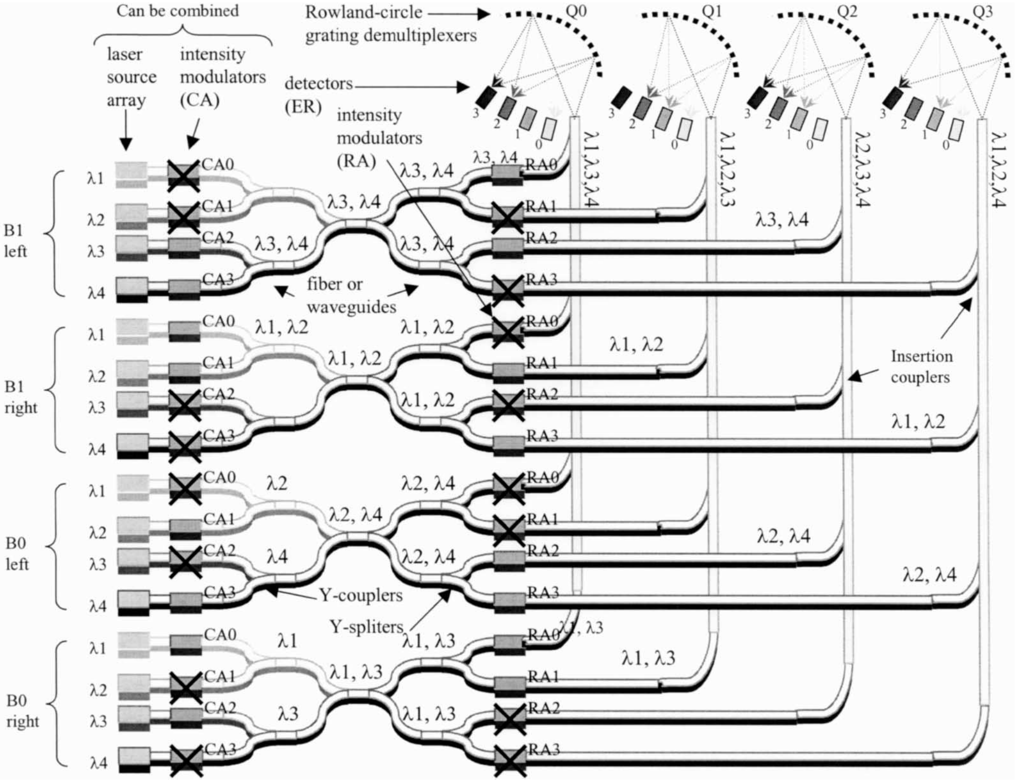

Fig. 3. Guided-wave implementation of the MESIGU. ×, opaque state of the modulators.

(New Focus, Inc.), was conducted. The MESIGU is able to provide a peak bit comparison rate of 310.4 Gbits/s. This rate represents a significant improvement in performance over that of any of its optical and even electronic counterparts. The current electronic CAM's (such as the NL877313 by NetLogic Microsystems) can perform 83×10^6 data comparisons/s, with a data width of 288 bits This translates to a processing rate of ~23.9 Gbits/s, which means the proposed 2-bit system is able to process 13 times faster than the current high-performance CAM. The MESIGU is also a scalable architecture. We can easily extend the number of words (in the CA and the RA) and the number of bits to provide a processing rate in the range of terabits per second (as in the EP^3IC, 82 Tbits/s). The input–output bandwidth requirement for the proposed 2-bit system is ~155 Gbits/s for both input and output.

The scalability of the MESIGU is limited by the optical power of the laser source, the sensitivity of the detector, the fan-out factor, and the inherent power loss by the nonideal components. The MESIGU is able to decrease the power loss by at least 3 dB from that of the EP^3IC with the elimination of polarization filter. This decrease means that the MESIGU can double the number of RA words, using the same photodetectors as the EP^3IC. Further improvements can also be made by use of more-efficient Y couplers in the MESIGU, since the Y-coupler junctions in the multiplexing process impose heavy power loss (typically −3 dB per junction). There is also an issue as to the scalability of the wavelength, which is determined mainly by the modulators (broadband modulation) and the sensitivity of the demultiplexers.

Although the MESIGU simplifies the design and the hardware used in the EP^3IC, it yields only half the data density of the EP^3IC. The dual-rail logic of the MESIGU reduces by half the data density of the EP^3IC. The T crossings (crossovers in waveguides) in the architecture may not be a problem in fiber-based systems, since such crossovers can be overlapped. However, these crossings will pose a challenge in planar waveguide systems because of fabrication difficulties and penalties. In conclusion, the MESIGU brings the optical high-performance CAM processing schemes closer to where they may actually be built and is competitive with its electronic counterparts in terms of size and performance.

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