IEICE TRANS. ELECTRON., VOL.E88–C, NO.9 SEPTEMBER 2005

PAPER *Special Section on Nanophotonics and Related Techniques*

Nanophotonic Computing Based on Optical Near-Field Interactions between Quantum Dots

Makoto NARUSE[†a)], **Tetsuya MIYAZAKI**[†], ***Members***, **Tadashi KAWAZOE**[††], **Suguru SANGU**[†††], ***Nonmembers***,
Kiyoshi KOBAYASHI[††††], ***Member***, **Fumito KUBOTA**[†], ***Fellow***, ***and*** **Motoichi OHTSU**[†††††], ***Member***

SUMMARY We approach nanophotonic computing on the basis of optical near-field interactions between quantum dots. A table lookup, or matrix-vector multiplication, architecture is proposed. As fundamental functionality, a data summation mechanism and digital-to-analog conversion are experimentally demonstrated using CuCl quantum dots. Owing to the diffraction-limit-free nature of nanophotonics, these architectures can achieve ultrahigh density integration compared to conventional bulky optical systems, as well as low power dissipation.

key words: *nanophotonics, optical signal processing, optical near-field, information processing, nanophotonic computing*

1. Introduction

To accommodate the continuously growing amount of data traffic in communication systems [1], optics is expected to further enhance the overall system performance by performing certain functional behavior [2]. In this regard, so-called all-optical packet switching has been thoroughly investigated. Also, the application of optical features, such as parallelism, in computing systems has been investigated since the 1970s [3], [4]. However, many technological difficulties remain to be overcome; one problem is the poor integrability of the hardware due to the diffraction limit of light, which is much larger than the gate width in VLSI circuits. This results in relatively bulky hardware configurations.

Nanophotonics, on the other hand, is free from the diffraction limit since it is based on local electromagnetic interactions between a few nanometric particles, such as quantum dots (QDs), via optical near-fields [5]. From an architectural perspective, this drastically changes the fundamental design rules of optical functional systems.

In this paper, we propose a nanophotonic computing architecture composed of table-lookup operations, as schematically shown in Fig. 1. A large amount of lookup-table (routing table) data can be recorded by configuring the sizes and positions of QDs, and by implementing the required logical operation mechanisms for each entry, based on near-field interactions. Since the internal device functions are based on uni-directional energy transfer via near-field interactions, which is prohibited for far-field light, as discussed in Sect. 3, input query data to the nanophotonic lookup table may be supplied globally by far-field light by tuning its operating frequency so that it does not interfere with the internal device operations.

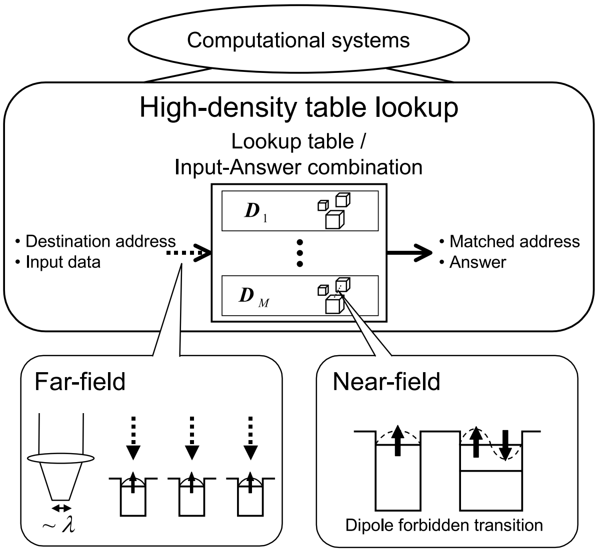

Fig. 1 An architecture for nanophotonic computing: High-density parallel table lookup based on nanophotonics. Internal device operation is based on near-field interactions between quantum dots, whereas input data can be either globally irradiated via far-field light or individually addressed through far- to near-field conversion.

This paper is organized as follows. In Sect. 2, we relate the table lookup operations and arbitrary digital computations to inner product operations with an appropriate data representation. Section 3 discusses their nanophotonic implementation. As an important sub-function, a data summation mechanism based on optical near-field interactions between QDs is shown. Also, its proof-of-principle experiment is demonstrated using CuCl QDs in a NaCl matrix. As an extension of the table lookup operation, or matrix-vector multiplication, Sect. 4 discusses digital-to-analog conversion by configuring the coupling strength between QDs. Its experimental verification is also shown. Finally, Sect. 5 concludes the paper.

Manuscript received December 1, 2004.
Manuscript revised April 30, 2005.

[†] The authors are with the National Institute of Information and Communications Technology, Koganei-shi, 184-8795 Japan.

[††] The author is with Japan Science and Technology Agency, Machida-shi, 194-0004 Japan.

[†††] The author is with Ricoh Co., Ltd., Yokohama-shi, 224-0035 Japan.

[††††] The author is with Tokyo Institute of Technology, Tokyo, 152-8551 Japan.

[†††††] The author is with the University of Tokyo, Tokyo, 113-8656 Japan.

a) E-mail: naruse@nict.go.jp

DOI: 10.1093/ietele/e88–c.9.1817

2. Nanophotonic Computing Architecture Based on High-Density Table Lookup

This section discusses the overall processing architecture. We begin with a concrete example of a packet forwarding application, which is an important function in routers; in this application, the output port for an incoming packet is determined based on a routing table. For such functions, a content addressable memory (CAM) [6] or its equivalent is used; in a CAM, an input signal (content) serves as a query to a lookup table and the output is the address of data matching the input. All optical means for implementing such functions have been proposed, for instance, by using planar lightwave circuits [7]. However, since we need separate optical hardware for each table entry if based on today's known methods, if the number of entries in a routing table is on the order of 10,000 or more, the overall physical size of the system becomes unfeasibly large. On the other hand, by using diffraction-limit-free nanophotonic principles, huge lookup table can be configured compactly.

First, we begin by relating the table lookup problem to an inner product operation. We assume an N-bit input signal $\boldsymbol{S} = (s_1, \cdots, s_N)$ and reference data $\boldsymbol{D} = (d_1, \cdots, d_N)$. Here the inner product $\boldsymbol{S} \bullet \boldsymbol{D} = \sum_{i=1}^{N} s_i \bullet d_i$ will provide a maximum value when the input perfectly matches the reference data. However, the inner product is, in fact, not enough to determine correct matching of the input and reference. This can be demonstrated as follows. Assume, for example, a 4-bit input $\boldsymbol{S} = (1010)$, and two items of reference data $\boldsymbol{D}_1 = (1010)$ and $\boldsymbol{D}_2 = (1110)$. Both inner products result in a value of 2, but the correctly matching data is only $\boldsymbol{D}_1$. That is to say, the exclusiveness of the matching operations should also be considered. Correct matching can be achieved by calculating also the inner product of the *inverted* input signal and reference data. Inversion is, however, a difficult function to implement optically. One possible option is to properly design the modulation format [8], for instance, by representing a logical level by two digits, such as Logic 1="10" and Logic 0="01." Then, an N-bit logical input is physically represented by $2N$ bits, which makes the inner product equivalent to the matching operation.

For packet data transfer, an operation known as longest prefix matching is important [9]. In this operation, a "don't care" state is required. In the above format, it can be simply coded by "11." Then, the resultant multiplication of a don't-care bit with an input bit will be 1 for either Logic 0 or 1.

Suppose that the reference data in the memory $\boldsymbol{D}_j$ ($j = 1, \cdots, M$) and the input $\boldsymbol{S}$ are represented in the above format. Then, the function of the CAM will be to derive j that maximizes $\boldsymbol{S} \bullet \boldsymbol{D}_j$. A nanophotonic implementation of such a function can be implemented in a highly dense form, as shown in Sect. 3. In addition, a large array of such inner product operations will allow a massively parallel processing system to be constructed.

Consequently, multiple inner products are equivalent to a matrix-vector multiplication, which is capable of implementing a wide range of parallel computations [4]. As a simple example, digital-to-analog conversion will be demonstrated by tuning the near-field interaction strength, as discussed in Sect. 4.

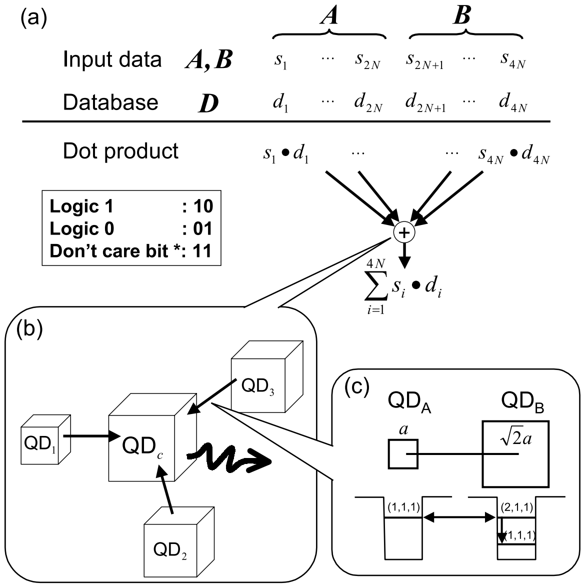

Fig. 2 (a) Inner product operation as a table lookup. (b) Summation mechanism in quantum dots. (c) Inter-dot interaction via an optical near-field.

Furthermore, arbitrary combinational logic can be reformulated as a table lookup operation; more specifically, any computation is equivalent to performing a lookup in a table where all possible input/answer combinations are prerecorded. For example, consider a two-input, two-bit ADD operation, $\boldsymbol{A} + \boldsymbol{B}$. In the ADD operation, the third-bit of the output (the carry bit) should be logical 1 when the second bits (that is, the 2^1 bit positions) of both inputs are 1, regardless of their first bits, that is, when $(\boldsymbol{A}, \boldsymbol{B}) = (1^*, 1^*)$. Therefore, following the data representation format introduced above (Logic 1 = 10, Logic 0 = 01, and don't care = 11), the table lookup entry $\boldsymbol{D}$ should be (10111011) so that any input combination satisfying $(\boldsymbol{A}, \boldsymbol{B}) = (1^*, 1^*)$ will provide a maximum inner product $\boldsymbol{S} \bullet \boldsymbol{D}$. This procedure is summarized in Fig. 2(a).

3. Data Summation Using Near-Field Interactions

As discussed in Sect. 2, the inner product operations are the key functionality of the present architecture. The multiplication of two bits, namely $x_i = s_i \bullet d_i$, has already been demonstrated by a combination of three quantum dots [10], [11]. Therefore, one of the key operations remaining is the summation, or data gathering scheme, denoted by Σx_i, where all data bits should be taken into account.

In known optical methods, wave propagation in free-space or in waveguides, using, for example, focusing lenses or fiber couplers, well matches such a data gathering scheme because the physical nature of propagating light is inherently suitable for global functionality such as global summation. However, the level of integration of these methods is restricted due to the diffraction limit of light. In nanophotonics, on the other hand, the near-field interaction is inherently physically local, although functionally global behavior is required.

Here we implement a global data gathering mechanism, or summation, based on the uni-directional energy flow via an optical near field, as schematically shown in Fig. 2(b), where surrounding excitations are transferred towards a quantum dot QD_C located at the center. As a fundamental case, we assume two quantum dots QD_A and QD_B, as shown in Fig. 2(c). The ratio of the sizes of QD_A and QD_B is $1 : \sqrt{2}$. There is a resonant quantized energy sublevel between those two dots, which are coupled by an optical near-field interaction [10]–[12]. Therefore, the exciton population in the (1,1,1)-level in QD_A is transferred to the (2,1,1)-level in QD_B [10], [12]. It should be noted that this interaction is forbidden for far-field light [13]. Since the intra-sublevel relaxation via exciton-phonon coupling is fast, the population is quickly transferred to the lower (1,1,1)-level in QD_B. Similar energy transfers may take place among the resonant energy levels in the dots surrounding QD_C so that energy flow can occur. One may worry that if the lower energy level of QD_B is occupied, another exciton cannot be transferred to that level due to the Pauli exclusion principle. Here, thanks again to the nature of the optical near-field interaction, the exciton population goes back and forth in the resonant energy level between QD_A and QD_B, which is called optical nutation [10]–[12]. Finally, both excitons can be transferred to QD_B. The lowest energy level in each quantum dot is coupled to a free photon bath to sweep out the excitation radiatively. The output signal is proportional to the (1,1,1)-level population in QD_B.

Numerical calculations were performed based on quantum master equations in the density matrix formalism. The model Hamiltonian of the coupled two-dot system is given by

$$H = \hbar \begin{pmatrix} \Omega_A & U \\ U & \Omega_B \end{pmatrix} \tag{1}$$

where $\hbar U$ is the optical near-field interaction, and $\hbar\Omega_A$ and $\hbar\Omega_B$ respectively refer to the eigenenergies of QD_A and QD_B. The equation of motion is given by the Liouville equation:

$$\dot{\rho}(t) = -\frac{i}{\hbar}[H, \rho(t)] \tag{2}$$

where ρ is the density operator. We used seven bases where either zero, one, or two excitons occupy the (1,1,1) level in QD_A, the (2,1,1) level in QD_B, and the (1,1,1) level in QD_B. Assuming inter-dot near-field coupling (U), exciton-phonon coupling (Γ), and relaxation to the radiation photon bath (γ_A for QD_A and γ_B for QD_B), within the Born-Markov approximation [14], we can derive multiple differential equations. In the following, we assume $U^{-1} = 50$ ps, $\Gamma^{-1} = 10$ ps, $\gamma_A^{-1} = 2\sqrt{2}$ ns, and $\gamma_B^{-1} = 1$ ns as a typical parameter set.

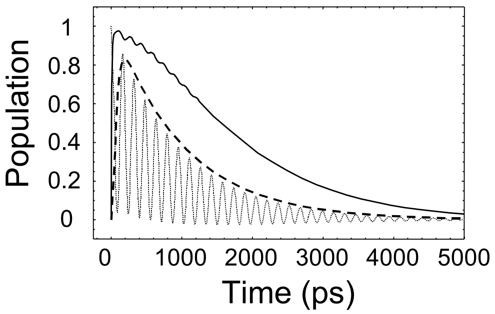

Fig. 3 Time evolution of the population of the lower level of QD_B in a two-exciton system (solid curve) and a one-exciton system (dashed curve). Dotted curve shows the population when QD_A has an exciton in a two-exciton system; Nutation is observed.

First, we consider an initial condition where there are two excitons in the system: one in QD_A and the other in QD_B (two-exciton system). The population of the (1,1,1)-level in QD_B is related to the output signal, whose time evolution is shown by the solid curve in Fig. 3. Incidentally, the population when QD_A has an exciton is denoted by the dotted curve in Fig. 3. Nutation is observed as expected since the lower level of QD_B is likely to be occupied and the inter-dot near-field interaction is faster than the radiative relaxation at each dot.

We then compare the population dynamics between one- and two-exciton systems. The dashed curve in Fig. 3 shows the time evolution of the population in the lower level of QD_B, where, as an initial condition, one exciton exists only in QD_A. Physically the output signal is considered to be the radiative relaxation from the lowest energy level of the output QD, which is related to integration of the population in the lower level of QD_B. By numerically integrating the population between 0 and 5 ns, we can obtain the ratio of the output signals between the two- and one-exciton systems, namely, 1.86:1, which reflects the number of initial excitons, or the summation mechanism.

A proof-of-principle experiment was performed to verify the nanoscale summation using CuCl quantum dots in a NaCl matrix, which has also been employed for demonstrating nanophotonic switches [10] and optical nano-fountains [15]. We selected a quantum dot arrangement where small QDs (QD_1 to QD_3) surrounded a "large" QD (QD_C), as schematically shown in Fig. 4(a). Here, we irradiate at most three light beams with different wavelength, 325 nm, 376 nm, and 381.3 nm, which respectively excite the quantum dots QD_1 to QD_3 having sizes of 1 nm, 3.1 nm, and 4.1 nm, respectively. The excited excitons are transferred to QD_C, and its radiation is observed by a near-field fiber probe. Notice the output signal intensity at a photon energy level of 3.225 eV in Fig. 4(b), which corresponds to a wavelength of 384 nm or a QD_C size of 5.9 nm. The intensity varies approximately as 1:2:3 depending on the number of excited QDs in the vicinity, as observed in Fig. 4(b). The spatial intensity distribution was measured by scanning the fiber probe, as shown in Fig. 4(c), where the energy is converged at the center. Hence, this architecture works as a summation mechanism, counting the number of input channels, based on exciton energy transfer via optical near-field interactions.

Such a quantum-dot-based data gathering mechanism is also extremely energy efficient compared to other optical methods such as focusing lenses or optical couplers. For example, the transmittance between two materials with refractive indexes n_1 and n_2 is given by $4n_1n_2/(n_1+n_2)^2$; this gives a 4% loss if n_1 and n_2 are 1 and 1.5, respectively. The transmittance of an N-channel guided wave coupler is $1/N$ from the input to the output if the coupling loss at each coupler is 3 dB. In nanophotonic summation, the loss is attributed to the dissipation between energy sublevels, which is significantly smaller. Incidentally, it is energy- and space-efficient compared to electrical CAM VLSI chips [16]–[18], as shown in Table 1.

We should also note, in terms of interconnections, that the input data should be commonly applied to all lookup table entries, which allows another possible interconnection mechanism. Since the internal functionality is based on energy transfer via optical near-field interactions and it is forbidden for far-field light, global input data irradiation, that is, broadcast interconnects, via far-field light may be possible; this is now being investigated [19].

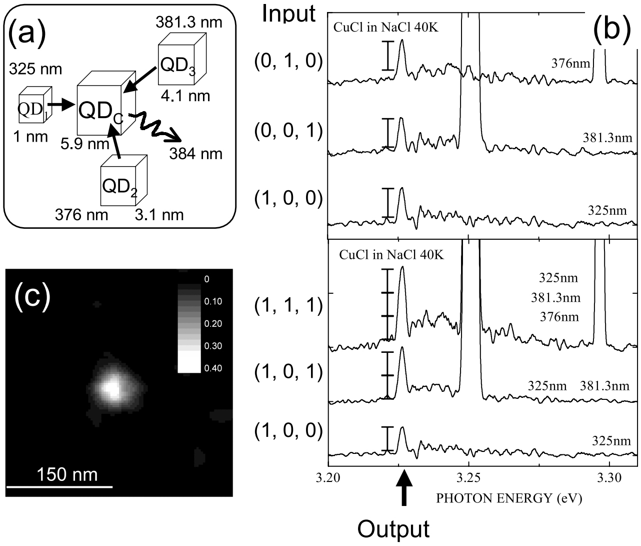

Fig. 4 Experimental results of the nanometric summation. (a) A quantum dot arrangement. (b) Luminescence intensity for three different numbers of excited QDs. (c) Spatial intensity distribution of the output photon energy.

Table 1 Power dissipation and cell size comparison with electrical CAM VLSI chips and optical waveguides.

	Power dissipation (fJ / bit / search)	Cell size (μm²)
CAM chip[16]	3.4	-
CAM chip[17]	2.1	17.54
CAM chip[18]	1.3	17.46
Optical waveguide	-	~ 1,000
Nanophotonic	0.0002	0.01

4. Digital-to-Analog Conversion Using Near-Field Interactions

In the summation mechanism shown in Sect. 3, the coupling strengths between the input QDs and the output QD is uniform. However, these coupling strengths can be independently configured, for instance, by modifying the relative distances. Theoretically, this corresponds to configuring U of the Hamiltonian in Eq. (1). For instance, consider three input QDs, QD_0 to QD_2, as schematically shown in Fig. 5(a). By choosing U^{-1} of 410 ps, 240 ps, and 50 ps between QD_0 to QD_2 and the output QD, respectively, the simulated time evolution of the output population is summarized in Fig. 5(b). The time integral of the output populations originating from QD_0 to QD_2 between 0 and 5 ns is approximately in a ratio of 1:2:4. This leads to a digital-to-analog conversion formula given by

$$d = 2^0 s_0 + 2^1 s_1 + 2^2 s_2 \tag{3}$$

where d is the output, and s_0, s_1, and s_2 represent the presence/absence of excitations in QD_0 to QD_2 respectively. Here each of the inputs s_i is optically applied to the system whose frequency is resonant with the (1,1,1)-level in QD_i. It should be noted that they are not coupled to the other QDs (i.e., input QD_j ($j \neq i$) and the output QD) since the corresponding energy levels are optically forbidden for the other QDs. Also, the initial state of the system is considered to be one in which an exciton is excited at each dot.

In the experiment, CuCl QDs in a NaCl matrix were used, as in Sect. 3, and three different input light frequencies were assigned to the three-bit input. Here, the output signal is considered to be the radiative relaxation from the lowest energy level of the output QD, which is observed with a near-field fiber probe at a wavelength of 384 nm. One re-

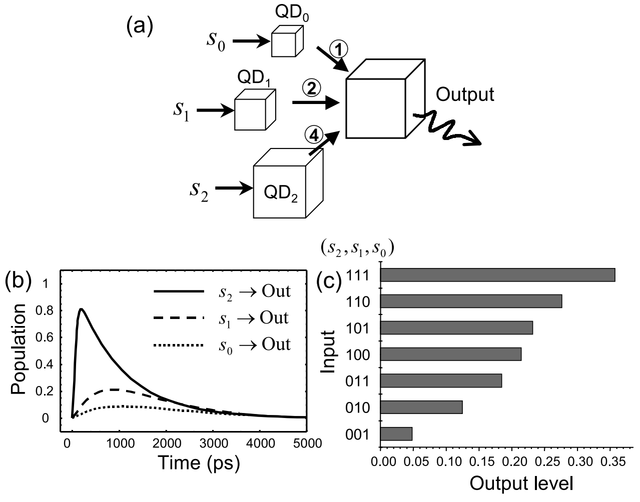

Fig. 5 (a) Digital-to-analog (DA) conversion. The near-field coupling is tuned so as to satisfy the relation for DA conversion. (b) Time evolution from each of the input bits to the output. (c) Experimental results of the output intensity level as a function of 3-bit input combinations.

mark here is that not every excited exciton produces the output signal; for instance there will be loss due to relaxation at each of the input QDs when the output energy level is occupied. However, such effects may not be serious since, as discussed in Sect. 3, nutation occurs among resonant energy levels and the relaxation rate at the output QD, which is the largest in the system in terms of size, is smaller than that at the input QDs. Figure 5(c) shows output signal intensity as a function of the presence (1) or absence (0) of the input excitation, as specified by (s_2, s_1, s_0), which were respectively 381.3 nm, 376 nm, and 325 nm. The output intensity is approximately linearly correlated to the input bit set combination, which indicates the validity of the digital-to-analog conversion mechanism. Compared to known optical approaches, such as those based on space-domain filtering and focusing lenses [3], [4], or optical waveguides and intensity filters [20], the nanophotonic approach achieves a significant higher spatial density.

5. Discussion

In summary, an architecture for nanophotonic computing is proposed; the architecture is based on table lookup using near-field interactions between quantum dots (QDs). As well as content addressable memories, digital logic and matrix-vector multiplication can be implemented in this architecture. As fundamental functional elements, a data summation mechanism and digital-to-analog conversion are presented, and their proof-of-principle experiments are demonstrated using CuCl QDs. Owing to its high spatial density and low power dissipation, a massive array of such functional components will be useful in applications such as massive table lookup operations in networking and information processing systems.

Generality of processing remains an open issue since it requires random access memories, and other design strategies, such as binary decision diagrams [21], are another possible candidates. Memory is also an extremely important subject for optical networks to replace the bulky optical fiber loops used for buffering [22]; the possibility of using nanophotonic devices in these applications is now being pursued [11]. The extremely high spatial density will also lead to novel system design concepts, for instance, in redundancy or fault tolerance [23]. In addition, further investigation of system application issues is indispensable, such as interconnections [24], [25], the fabrication limitations of nanostructures [26], and new applications unachievable by other technologies.

References

[1] 2004 WHITE PAPER, Information and Communications in Japan, Ministry of Internal Affairs and Communications (MIC), Japan.

[2] S. Yao, B. Mukherjee, and S. Dixit, “Advances in photonic packet switching: An overview,” IEEE Commun. Mag., vol.38, no.2, pp.84–94, 2000.

[3] J.W. Goodman, A.R. Dias, and L.M. Woody, “Fully parallel, high-speed incoherent optical method for performing discrete Fourier transforms,” Opt. Lett., vol.2, pp.1–3, 1978.

[4] P.S. Guilfoyle and D.S. McCallum, “High-speed low-energy digital optical processors,” Opt. Eng., vol.35, pp.436–442, 1996.

[5] M. Ohtsu, K. Kobayashi, T. Kawazoe, S. Sangu, and T. Yatsui, “Nanophotonics: Design, fabrication, and operation of nanometric devices using optical near fields,” IEEE J. Sel. Top. Quantum Electron., vol.8, no.4, pp.839–862, 2002.

[6] H. Liu, “Routing table compaction in ternary CAM,” IEEE Microw., vol.22, no.1, pp.58–64, 2002.

[7] A. Grunnet-Jepsen, A.E. Johnson, E.S. Maniloff, T.W. Mossberg, M.J. Munroe, and J.N. Sweetser, “Fibre Bragg grating based spectral encoder/decoder for lightwave CDMA,” Electron. Lett., vol.35, pp.1096–1097, June 1999.

[8] M. Naruse, H. Mitsu, M. Furuki, I. Izumi, Y. Sato, S. Tatsuura, M. Tian, and F. Kubota, “Terabit all-optical logic based on ultrafast two-dimensional transmission gating,” Opt. Lett., vol.29, pp.608–610, 2004.

[9] K. Kitayama and M. Murata, “Versatile optical code-based MPLS for circuit, burst, and packet switchings,” IEEE J. Lightwave Technol., vol.21, no.11, pp.2753–2764, 2003.

[10] T. Kawazoe, K. Kobayashi, S. Sangu, and M. Ohtsu, “Demonstration of a nanophotonic switching operation by optical near-field energy transfer,” Appl. Phys. Lett., vol.82, pp.2957–2959, 2003.

[11] S. Sangu, K. Kobayashi, A. Shojiguchi, and M. Ohtsu, “Logic and functional operations using a near-field optically coupled quantum-dot system,” Phys. Rev. B, vol.69, pp.115334-1–13, 2004.

[12] T. Kawazoe, K. Kobayashi, J. Lim, Y. Narita, and M. Ohtsu, “Direct observation of optically forbidden energy transfer between CuCl quantum cubes via near-field optical spectroscopy,” Phys. Rev. Lett., vol.88, pp.067404-1–4, 2002.

[13] Z.K. Tang, A. Yanase, T. Yasui, Y. Segawa, and K. Cho, “Optical selection rule and oscillator strength of confined exciton system in CuCl thin films,” Phys. Rev. Lett., vol.71, pp.1431–1434, 1993.

[14] H.J. Carmichael, Statistical Methods in Quantum Optics I, Springer-Verlag, Berlin, 1999.

[15] T. Kawazoe, K. Kobayashi, and M. Ohtsu, “Optical nanofountain: A biomimetic device that concentrates optical energy in a nanometric region,” Appl. Phys. Lett., vol.86, pp.103102-1–3, 2005.

[16] I. Arsovski and A. Sheikholeslami, “A current-saving match-line sensing scheme for content-addressable memories,” 2003 IEEE International Solid-State Circuits Conference, Digest of Technical Papers, vol.1, pp.304–494, 2003.

[17] I. Arsovski, T. Chandler, and A. Sheikholeslami, “A ternary content-addressable memory (TCAM) based on 4T static storage and including a current-race sensing scheme,” IEEE J. Solid-State Circuits, vol.38, no.1, pp.155–158, 2003.

[18] P.-F. Lin and J.B. Kuo, “A 1-V 128-kb four-way set-associative CMOS cache memory using wordline-oriented tag-compare (WLOTC) structure with the content-addressable-memory (CAM) 10-transistor tag cell,” IEEE J. Solid-State Circuits, vol.36, no.4, pp.666–675, 2001.

[19] M. Naruse, F. Kubota, T. Kawazoe, S. Sangu, K. Kobayashi, and M. Ohtsu, “Optical interconnects using optical far- and near-field interactions for high-density data broadcasting,” Conference on Lasers and Electro-Optics (CLEO) 2005, paper CWF6.

[20] T. Saida, K. Okamamoto, K. Uchiyama, K. Takiguchi, T. Shibata, and A. Sugita, “Integrated optical digital-to-analogue converter and its application to pulse pattern recognition,” Electron. Lett., vol.37, pp.1237–1238, 2001.

[21] S.B. Akers, “Binary decision diagram,” IEEE Trans. Comput., vol.C-27, no.6, pp.509–516, 1978.

[22] D.K. Hunter, M.C. Chia, and I. Andonovic, “Buffering in optical packet switches,” IEEE J. Lightwave Technol., vol.16, no.12, pp.2081–2094, 1998.

[23] K. Nikolic, A. Sadek, and M. Forshaw, “Fault-tolerant techniques for nanocomputers,” Nanotechnology, vol.13, pp.357–362, 2002.

[24] T. Yatsui, M. Kourogi, and M. Ohtsu, “Plasmon waveguide for op-

tical far/near-field conversion," Appl. Phys. Lett., vol.79, pp.4583–4585, 2001.
[25] J. Takahara, Y. Suguru, T. Hiroaki, A. Morimoto, and T. Kobayashi, "Guiding of a one-dimensional optical beam with nanometer diameter," Opt. Lett., vol.22, pp.475–477 1997.
[26] T. Yatsui, S. Takubo, J. Lim, W. Nomura, M. Kourogi, and M. Ohtsu, "Regulating the size and position of deposited Zn nanoparticles by optical near-field desorption using size-dependent resonance," Appl. Phys. Lett., vol.83, pp.1716–1718, 2003.

Makoto Naruse was born in Tokyo, Japan, in 1971. He received the B.E., M.E., and Dr. Eng. degrees from the University of Tokyo in 1994, 1996, and 1999, respectively. From 1999 to 2000, he was a postdoctoral researcher of the Japan Society for the Promotion of Science. From 2000 to 2002, he was a research associate at the University of Tokyo. In 2002, he joined the Ultrafast Photonic Network Group at the National Institute of Information and Communications Technology (formerly the Communications Research Laboratory). From 2003, he is a senior researcher. From 2001 to 2005, he was concurrently serving as a researcher of the PRESTO program of the Japan Science and Technology Agency. He is currently engaged in optical communication and information processing systems based on novel optical devices and architectures. He received an Inoue Research Award for Young Scientist from the Inoue Foundation for Science and a Research Award from Research Foundation for Opto-Science and Technology in 2000. Dr. Naruse is a member of the OSA, the Japan Society of Applied Physics and the Society of Instrument and Control Engineers.

Tetsuya Miyazaki was born in Chiba, Japan, in 1962. He received the B.S. degree in physics from the University of Tsukuba, Ibaraki, Japan, in 1985 and the M.S. and Dr.Eng. degrees in information processing from the Tokyo Institute of Technology, Tokyo, Japan, in 1987 and 1997, respectively. In 1987, he joined KDDI Research and Development (R&D) Laboratories, Saitama, Japan, where he worked on coherent optical communications. From 1993 to 1996, he was with ATR Optical and Radio Communications Research Laboratories, where he worked on fiber amplifiers for optical inter-satellite links. From 1996 to 2002, he was with KDDI R&D Laboratories, where he was engaged in work on WDM optical networks. Since April 2002, he has been with Communications Research Laboratory (currently NICT) where he is involved in research on ultra-fast photonic networks. Currently, he is group leader of the ultra-fast photonic network group. Dr. Miyazaki is a member of the IEEE Laser and Electro-Optic Society (IEEE LEOS).

Tadashi Kawazoe was born in Kochi in 1967. He received the B.E., M.E., and Ph.D. degrees in physics from University of Tsukuba, Tsukuba, Japan, in 1990, 1993, and 1996, respectively. He is a researcher at Solution Oriented Research for Science and Technology (SORST) project of Japan Science and Technology Agency. In 1996, he joined the Faculty of Engineering, Yamagata University, Yamagata, Japan, as a Research Associate, engaged in research on nonlinear optical materials and devices. Since April 2000, he has been with Japan Science and Technology Agency. His current research interests are in the areas of optical properties of nano materials, optical near field, and nanophotonic devices. Dr. Kawazoe is a member of the Japan Society of Applied Physics and the Physical Society of Japan.

Suguru Sangu was born in Hokkaido, Japan, in 1971. He received the B.E. degree from the Muroran Institute of Technology, Hokkaido, Japan, in 1994, and the M.E. and Ph.D. degrees in electronics and information engineering from Hokkaido University, Hokkaido, Japan, in 1996 and 1999, respectively. From 1999 to 2003, he joined the "Localized Photon" project for the Exploratory Research for Advanced Technology (ERATO) at the Japan Science and Technology Agency. Since 2003, he has been a Researcher of the Research and Development Center, Ricoh Company Ltd. His current research interests are the theory on near-field optics and its application to nano-photonics. Dr. Sangu is a member of the Japan Society of Applied Physics.

Kiyoshi Kobayashi was born in Okayama in 1953. He received the D.S. degree in physics from the University of Tsukuba, Tsukuba, Japan, in 1982. After graduation, he joined IBM Japan as a Research Staff Member at Tokyo Research Laboratory, Tokyo, Japan. Since 1998, he has been the theoretical group leader of the "Localized Photon" project for the Exploratory Research for Advanced Technology (ERATO) at the Japan Science and Technology Agency, Tokyo. Since 2004, he has been a Professor with the 21 Century Center of Excellence Program, Nanometer-scale Quantum Physics, Department of Physics, Tokyo Institute of Technology, Tokyo, Japan. His main fields of interest are quantum optical near-field theory and its application to nano/atom photonics. Dr. Kobayashi is a member of the Physical Society of Japan, the Japan Society of Applied Physics, and the American Physical Society.

Fumito Kubota received a B.E. in Instrumentation Engineering from Keio University, Japan and a Ph.D. in Computer Science and Electronics from the Kyushu Institute of Technology, Japan. He joined the Radio Research Laboratories, Ministry of Posts and Telecommunications (presently National Institute of Information and Communications Technology (NICT)). Since then, he has been involved in research on mobile communications and advanced networks. From 1982 through 1983, he engaged in research on digital mobile communications at the Nancy 1 University in France. Currently, he is a Research Supervisor in the Information and Network Systems Department at NICT. Concurrently, he functions in the capacity of Guest Professor at both the National Institute of Multimedia Education (NIME) since 1996 and the Japan Advanced Institute of Science and Technology (JAIST), Hokuriku since 1999. He is a member of IEEE.

Motoichi Ohtsu received the B.E., M.E., and Dr.E. degrees in electronics engineering from the Tokyo Institute of Technology, in 1973, 1975, and 1978, respectively. In 1978, he was appointed a Research Associate, and in 1982, he became an Associate professor at the Tokyo Institute of Technology. From 1986 to 1987, while on leave from the Tokyo Institute of Technology, he joined the Crawford Hill Laboratory, AT&T Bell Laboratories. In 1991, he became a Professor at the Tokyo Institute of Technology. In 2004, he moved to the University of Tokyo. Since 1993, he has been concurrently the leader of the “Photon Control” project of the Kanagawa Academy of Science and Technology. Since 1998, he has been concurrently the leader of the “Localized Photon” project of ERATO. Since 2002, he is a leader of the national project on “Ultrahigh density optical storage” sponsored by METI. He has written over 320 papers and received 87 patents. He is the author and co-author of 39 books. In 2000, he was the President of the IEEE/LEOS Japan Chapter. From 2000, he is an executive director of the Japan Society of Applied Physics. In 2001, he served as a Technical Program Co-chair for the 4th CLEO/PR01. He has been a tutorial lecturer o the SPIE and the OSA. He is a member of several boards of the MEXT, METI, and so on. Prof. Ohtsu is a Fellow of the OSA, a senior member of IEEE, and member of several academic societies. He has been awarded ten prizes from academic institutions, including the I. Koga Gold Medal of URSI in 1984, the Japan IBM Science Award in 1988, two awards from the JSAP in 1982 and 1990, and the Inoue Science Foundation Award in 1999. In 2004, he was awarded a purple ribbon medal from Japanese government.