Fig. 2 shows the CW light output power against current characteristics at 20°C. The threshold current (density) is 57 mA ($\simeq 3{\cdot}2\,kA/cm^2$), which is as low as that for a 650 nm-band laser diode with a double-heterostructure (DH structure) [1]. We believe this to be the lowest ever value for a 630 nm-band AlGaInP laser diode. The maximum CW output power is ~ 15 mW, and this is limited by the COD (catastrophic optical damage) of this structure. The slope efficiency of a laser diode is as high as 0·4 W/A for a 670 nm-band laser diode with a DH structure [8]. The maximum CW operating temperature is 50°C.

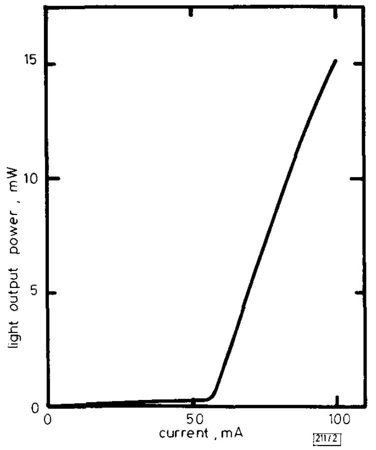

Fig. 2 *CW light output power against current characteristics*
20°C, uncoated

Fig. 3 shows the oscillation spectrum for laser diodes at 20°C, 8 mW under CW operation. The oscillation wavelength is 635·6 nm.

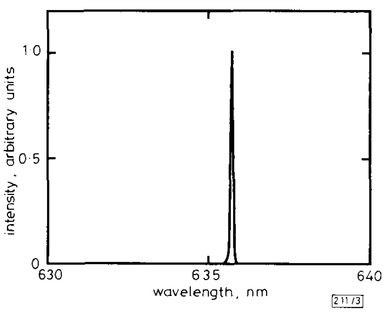

Fig. 3 *Lasing spectrum*
20°C, CW, 8 mW, $\lambda_L = 635{\cdot}6$ nm

Fig. 4 shows the far-field patterns of the laser diodes. Stable fundamental transverse-mode operation is obtained up to 8 mW. The beam divergence perpendicular to and parallel with the junction at a light output power of 8 mW are 30 and 8·5°, respectively.

In conclusion, the low-threshold 630 nm-band laser diodes have been achieved by using AlGaInP lasers with an MQW active layer. The threshold current was as low as 57 mA at 20°C, and the oscillation wavelength was 635·6 nm at 8 mW. Stable fundamental transverse-mode operation was obtained up to 8 mW. The maximum light output power was 15 mW at 20°C. The increased light output power of the lasers may be realised by introducing the current-blocking region near the facets, and by forming AR and HR coatings for the front and rear facets, respectively.

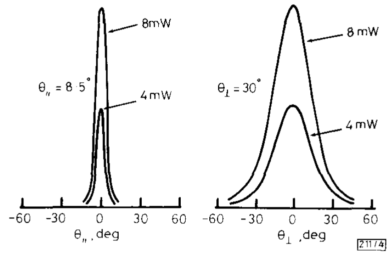

Fig. 4 *Far-field patterns*
20°C

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References

1 HAMADA, H., SHONO, M., HONDA, S., HIROYAMA, R., YODOSHI, K., and YAMAGUCHI, T.: 'AlGaInP visible laser diodes grown on misoriented substrates', *IEEE J. Quantum Electron.*, 1991, **QE-27**, pp. 1483–1490

2 ITAYA, K., ISHIKAWA, M., and UEMATSU, Y.: '636 nm room temperature CW operation by heterobarrier blocking structure InGaAlP laser diodes', *Electron. Lett.*, 1990, **26**, pp. 839–840

3 KOBAYASHI, K., UENO, Y., HOTTA, H., GOMYO, A., TADA, K., HARA, K., and YUASA, T.: '632·7 nm CW operation (20°C) of AlGaInP visible laser diodes fabricated on (001) 6° off toward (110) GaAs substrate', *Jpn. J. Appl. Phys.*, 1990, **29**, pp. L1669–L1671

4 VALSTER, A., VAN DER POEL, C. J., FINKE, M. N., and BOERMANS, M. J. B.: 'Low threshold current density ($760\,A/cm^2$) and high power (45 mW) operation of strained $Ga_{0{\cdot}42}In_{0{\cdot}58}P$ multiquantum well laser diodes emitting at 632 nm', *Electron. Lett.*, 1992, **28**, pp. 144–145

5 TANAKA, T., YANAGISAWA, H., KAKIBAYASHI, H., MINAGAWA, S., and KAJIMURA, T.: 'Uniform p-type impurity-doped multiquantum well AlGaInP semiconductor lasers with a lasing wavelength of 633 nm at 20°C', *Appl. Phys. Lett.*, 1991, **59**, pp. 1943–1945

6 KATSUYAMA, T., YOSHIDA, I., SHINKAI, J., HASHIMOTO, J., and HAYASHI, H.: '637 nm cw operation of low threshold current AlGaInP strained single quantum well laser diodes'. Extended Abstracts Int. Conf. on Solid State Devices and Materials, 1991, pp. 117–119

7 HAMADA, H., HONDA, S., SHONO, M., HIROYAMA, R., YODOSHI, K., and YAMAGUCHI, T.: 'Activation of Zn acceptors in AlGaInP epitaxial layers grown on misoriented substrates by metal organic chemical vapour deposition', *Electron. Lett.*, 1992, **28**, (6), pp. 585–587

8 KOBAYASHI, K., KAWATA, S., FUJII, H., HINO, I., GOMYO, A., HOTTA, H., and SUZUKI, T.: 'Transverse mode stabilised 670 nm AlGaInP visible-light laser diodes'. Proc. SPIE, Los Angeles, 1988, Vol. 898, pp. 84–88

SOLVING SORTING AND RELATED PROBLEMS BY QUADRATIC PERCEPTRONS

Y.-H. Tseng and J.-L. Wu

Indexing term: Neural networks

A quadratic perceptron has a polynomial of order 2 as its discriminant function. The Letter shows that it can be used to solve sorting, MIN, MAX (i.e. winner-take-all), and non-binary majority problems all in constant time.

Introduction: Among all computational models studied over the past, sorting appears to be a vital operation included as a primitive in many computing tasks. Previous work on the application of neural networks to sorting problems used the Hopfield model and multilayer perceptrons for constant-time computing [1–3]. In this Letter, the perceptron networks with quadratic polynomials as discriminant functions are used to solve sorting and its related problems, namely winner-take-all and nonbinary majority. The basic idea used in constructing a neural network to solve these problems is to express the solution in logic forms and then convert them into a set of discriminant functions. The resulting networks have low network complexity and short propagation delay, making them applicable as primitives of more complex computations.

The output function of a general perceptron can be described as

$$z = \mathrm{sgn}_0[g(X)] \tag{1}$$

In eqn. 1, $X = [x_1, x_2, \ldots, x_n] \in R^n$ is the network input; sgn_0 is a dichotomy function: $\mathrm{sgn}_0(a) = 1$ if $a > 0$, 0 if $a \le 0$, and g, the so called discriminant function, is an rth-order polynomial:

$$g(X) = w_1 f_1(X) + w_2 f_2(X) + \ldots + w_N f_N(X) + w_0 \tag{2}$$

where w_i are called weights and each product term $f_i(X)$ is of the form

$$x_{k_1}^{n_1} x_{k_2}^{n_2} \ldots x_{k_r}^{n_r} \tag{3}$$

$k_1, k_2, \ldots, k_r \in \{1, \ldots, n\}$ and $n_1, n_2, \ldots, n_r$ are integers. A linear perceptron has a discriminant function of order $r = 1$. A perceptron with $r = 2$ is called a quadratic perceptron, whose discriminant is also called a gating activation function in Reference 4 because the two variables in a product term can be seen as one gates the other. The above perceptron outputs binary values. Because a number can always be coded in binary form, if we allow a perceptron without using the dichotomy function, it would be more concise in representing the neural network solutions for the problems considered below.

Sorting networks: An unordered sequence $X = \{x_1, x_2, \ldots, x_n\}$ of real numbers can be sorted into an ordered sequence $S = \{s_0, s_1, \ldots, s_{n-1}\}$ by first determining the ranks of the numbers and then outputting them according to their ranks. The rank of number x_i is the number of elements in S following x_i. It can thus be expressed as

$$R(x_i) = \sum_{j=1}^{n} \mathrm{sgn}_0(x_i - x_j) \tag{4}$$

The smallest number has rank 0, the second is of rank 1, and so on. This rank will lead to a sorted sequence in increasing order and is thus called an increasing rank. In the same way, we can define a decreasing rank to result in a decreasing sequence as follows:

$$R^*(x_i) = \sum_{j=1}^{n} \mathrm{sgn}_0(x_j - x_i) \tag{5}$$

The above rank function results in a two-layer network: the first layer is a set of n linear perceptrons each of which has only two inputs; the second layer performs linear sums of the comparison results. These are perceptrons without the dichotomy function and thus their outputs can be immediately directed to the next layer.

The next step is to output the number with rank k to the correct position. A direct translation of this operation into a logic expression takes the form

$$s_k = \sum_{i=1}^{n} \mathrm{EQ}\,[k = R(x_i)]x_i \tag{6}$$

where EQ $(s = t)$ is a predicate, EQ $= 1$ if $s = t$ and EQ $= 0$ if $s \ne t$. The expression is further converted into a form implementable by quadratic perceptrons:

$$s_k = \sum_{i=1}^{n} \{\mathrm{sgn}_0[k + 1 - R(x_i)] + \mathrm{sgn}_0[R(x_i) - k + 1] - 1\}x_i \tag{7}$$

It can be seen that the expression in the braces is 1 if $k - 1 \le R(x_i) \le k + 1$ and 0 if $R(x_i) > k + 1$ or $R(x_i) < k - 1$, exactly meets the requirement of the predicate EQ. The resulting sorting network is shown in Fig. 1.

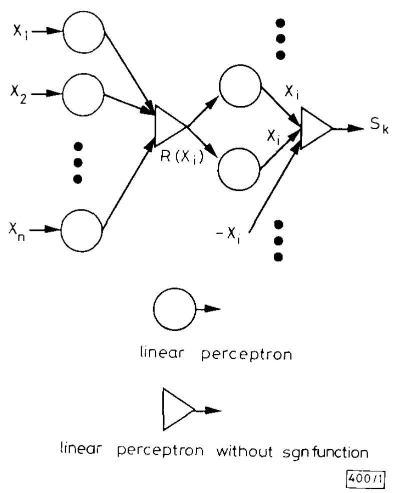

Fig. 1 *Proposed sorting network*

This Figure shows the part that computes the kth element in the sorted sequence

In parallel computing, an algorithm is often evaluated by a cost function defined as the product of hardware complexity and computational complexity [5]. In this sorting network, it requires $O(n^2)$ connections but constant-time computation. Thus its cost is $O(n^2)$. Although it is not cost optimal, which should be $O(n \log n)$, it has a simple structure where most of the connections are local.

Winner-take-all networks: Winner-take-all is an important operation in neural networks. It is usually solved in the form of fully connected recurrent networks [6]. The disadvantages of this approach are indefinite convergence time and inaccuracy [7]. With the idea of the above sorting network, winner-take-all problems can be solved accordingly. We consider the problem in two versions: MIN, select the minimum in sequence X; MAX, the maximum.

The MIN network, computing the MIN operation, can be derived by choosing the increasing rank defined in eqn. 4 and the first output s_0 of the sorting network. If the index instead of the value is needed, s_0 can be modified to output the index of the minimum number:

$$MIN = s_0 = \sum_{i=1}^{n} \mathrm{EQ}\,[0 = R(x_i)]i \tag{8}$$

The MAX network can be obtained similarly by choosing the decreasing rank in eqn. 5 and the first output s_0.

The proposed winner-take-all network requires constant-time computation and has none of the disadvantages mentioned above.

Nonbinary majority: Binary majority operation is a linearly separable problem and can be trivially solved by a linear perceptron by summing all its inputs [8]. However, the solution for the majority of nonbinary inputs is not so obvious without the help of the MAX network described above. The majority of m candidates cast by n voters is computed by a network which first counts the number of votes for each candidate and then feeds these numbers to the MAX network. The votes for candidate i are denoted as V_i, for $i = 1, 2, \ldots, m$, and

$$V_i = \sum_{j=1}^{n} \mathrm{EQ}\,(i = x_j) \qquad i = 1, 2, \ldots, m \tag{9}$$

The set of numbers $\{V_1, V_2, \ldots, V_m\}$ is then fed to the MAX network to result in a correct output. The constant-time majority network can be applied to decode those majority-decodable codes of the nonbinary case [9], for example.

Conclusion: We have presented efficient neural network solutions to sorting and related problems which are important primitives for neural networks themselves and other computation models. The main idea used in this approach is to convert the solution, expressed in logic form, into a set of discriminant functions of the perceptrons. This is quite a systematic method for constructing neural networks in solving problems because it has about the same level of complexity as writing an algorithm.

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References

1 TAKEFUJI, Y., and LEE, K.-C.: 'A two-step parallel sorting algorithm based on neural networks', *J. Neural Network Computing*, 1990, pp. 30–32

2 CHEN, W.-T., and HSIEH, K.-R.: 'A neural sorting network with O(1) time complexity'. Int. Joint Conf. on Neural Networks, 1990, pp. I87–I94

3 SIU, K.-Y., and BRUCK, J.: 'Neural computation of arithmetic functions', *Proc. IEEE*, 1990, **8**, (10), pp. 1661–1675

4 WILLIAMS, R. J.: 'The logic of activation functions', *in* RUMELHART, D. E., and PDP research group: 'Parallel distributed processing' (MIT Press, Cambridge, 1986)

5 SELIM G. AKL: 'The design and analysis of parallel algorithms' (Prentice-Hall, 1989)

6 LIPPMAN, R. P.: 'An introduction to computing with neural nets', *IEEE ASSP Mag.*, April 1987, pp. 4–22

7 CHIUEH, T.-D.: 'Pattern classification and associative recall by neural networks'. PhD dissertation, California Institute of Technology, USA, 1989

8 WIDROW, B., and WINTER, R.: 'Neural nets for adaptive filtering and adaptive pattern recognition', *Computer Magazine*, March 1988, pp. 25–39

9 BLAHUT, R. E.: 'Theory and practice of error control codes' (Addison-Wesley, 1983)

PICOSECOND SQUARE PULSE GENERATION USING NONLINEAR FIBRE LOOP MIRROR

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Indexing terms: Pulse generation, Nonlinear optics

Square pulses with controllable picosecond durations have been generated from a CW input signal in the region of $1{\cdot}5\,\mu m$ by using switching in a nonlinear loop mirror. The square pulses are generated in synchronism with a pulsed driver which can be a noise burst. Shaped pulses have also been derived using this technique.

The nonlinear ring interferometer [1] in fibre form [2] has been extensively studied with particular emphasis on ultrafast, all-optical switching and has been successfully demonstrated for both silicon and nonsoliton pulse inputs, in various geometries [3, 4]. For nonsoliton pulses, intensity dependent switching in most cases gives rise to fragmentation of the switched pulse. Square pulses do not exhibit this characteristic and consequently are preferable for some applications. Here we describe a simple technique to generate square pulses or shaped pulses, based on two wavelength operation of a nonlinear loop mirror [5, 6]. The pulses to be generated are derived from a CW input signal, driven by a pulse or noise burst derived from a laser source, such that the generated pulses are in time synchronism with the driver. In the work reported here the derived square pulses had durations of 35 ps.

A schematic diagram of the experimental arrangement is shown in Fig. 1. The pulse formation mechanism is based on the switching of a nonlinear Sagnac interferometer, which has been described previously [6–8]. Simply, in the absence of a switching pulse the transmission through the interferometer, for a low level signal (at a wavelength where the coupler has a 3 dB splitting ratio), is zero. In the presence of the switching pulse (at a wavelength where the coupler is imbalanced), through crossphase modulation, the signal experiences a net phase disturbance and is transmitted. The duration of the transmitted signal is dependent on the duration of the switching pulse and the relative group delay dispersion at the signal and switching wavelengths. Where the tracking is perfect the switched pulse will have a duration equal to that of the switching pulse. In the presence of complete walkoff, the switched pulse experiences a constant phase shift over its duration (apart from the rising and falling edges), generating a square pulse, the duration of which depends on the magnitude of the dispersions and loop length. Similarly, by mixing fibres with different dispersions within the loop, various shaped pulses can be generated.

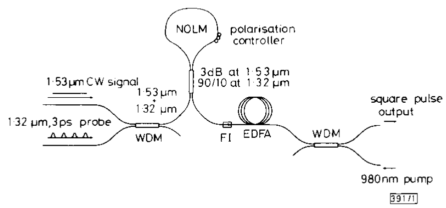

Fig. 1 *Schematic diagram of experimental setup*

The switching pulse was derived from the fibre-grating pair compressed output of a mode-locked Nd : YAG laser operating at $1{\cdot}32\,\mu m$. This generated 3 ps pulses at 100 MHz, allowing an average power of up to 100 mW in the fibre. The signal, tunable around $1{\cdot}53\,\mu m$, was obtained from a CW erbium fibre laser or a semiconductor laser, with maximum average powers of 30 mW and 1 mW obtained in the fibre, respectively. Signal and switching pulse were combined via a WDM and launched into the nonlinear optical loop mirror formed from a coupler with a 50 : 50 splitting ratio at $1{\cdot}53\,\mu m$ and 90 : 10 at $1{\cdot}32\,\mu m$. Various lengths of fibre with different dispersion minima were used within the loop, depending on the required output pulse shape. The switched pulse was passed through an in-line Faraday isolator (FI) and then amplified in a 15 m length of standard Al_2O_3–GeO_2–SiO_2 based, erbium-doped, singlemode fibre, which was pumped in a counter-propagating geometry at 980 nm via the exit WDM. Use of the amplifier outside the loop rather than inside, as in the case of so called NALMs, reduces noise problems. The amplified, generated pulse shape exited the other port of the WDM with average powers in the milliwatt range and was detected using an optical sampling oscilloscope and scanning spectrograph.

For square pulse generation, the fibre used within the loop was 20 m long with a dispersion minimum at $1{\cdot}32\,\mu m$. At the operating wavelengths and from the dispersive parameters of the fibre, a square pulse shape of 30 ps pulse duration was predicted (see Fig. 2*a*). This takes into account the finite response time of the optical sampling oscilloscope detector and the response function of the NOLM. Experimentally, a square pulse of approximately 34 ps was recorded as shown in Fig. 2*b*. This generated pulse was in time synchronism with the driving pulse. By modifying the fibre-grating arrangement, it is possible to generate noise bursts. By allowing total walk through of the noise burst, constant phase square pulses can still be generated. Because diode laser sources can be used to give rise to switching [8], it should be possible to use noise bursts from diode lasers to generate square pulses.

Replacing the fibre in the loop by a 10 m piece with a dispersion minimum at $1{\cdot}45\,\mu m$ and tuning the CW diode laser source, allowed perfect tracking between switching pulse and signal disturbance. This permitted the generation of