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All-Optical Buffering Using Laser Neural Networks

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Abstract—**We demonstrate an all-optical buffering method that can handle contention of three optical packets. We have employed a laser neural network as an all-optical arbiter that decides whether packet contention takes place. The laser neural network drives a wavelength routing switch that is used to route the data packets into fiber delay lines. Experimental results are presented.**

Index Terms—**Buffer memories, optical fiber communication, optical fiber delay lines, packet switching.**

I. INTRODUCTION

OPTICAL BUFFERING technology is receiving considerable attention as a result of the development of optical packet switches [1]. Examples are presented in [2] where optical buffering was realized by using electronically controlled wavelength routing switches in combination with optical delay lines. In [3], an all-optical buffering concept is demonstrated in which an optical loop controlled by wavelength converters is employed to realize a variable optical delay, and in [4] an all-optical buffering concept is demonstrated in which buffering is realized by using an optical threshold function in combination with a wavelength routing switch. The functionality of the optical threshold function is twofold: it acts as an arbiter to decide whether packet contention takes place, and it also controls a wavelength routing switch that is made from a wavelength converter, in combination with a demultiplexer. The optical threshold function that was used in [4] can only handle the contention of two packets. In this letter, we present an all-optical buffering concept that can handle multipacket contention, by using an all-optical arbiter that is based on a laser neural network (LNN) [5], [6]. The LNN replaces the role of the optical threshold function in [4] and acts as a nonlinear wavelength controller. We demonstrate experimentally that it is possible to route optical packets into optical buffers by using an LNN that controls a wavelength routing switch.

II. OPERATING PRINCIPLE

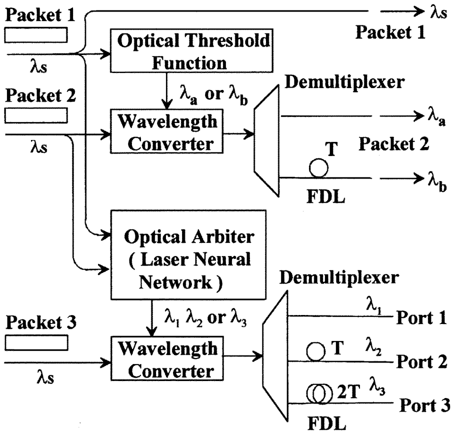

Fig. 1. Functional scheme of the all-optical buffer concept and the truth table of the optical arbiter (LNN) that is required to handle three packets contention. FDL: fiber delay line. T: the delay time equal to one packet length.

TABLE I
TRUTH TABLE OF LNN FOR BUFFERING PURPOSE

Packet 1	Packet 2	Output
0	0	λ_1
1	0	λ_2
0	1	λ_2
1	1	λ_3

The optical buffering concept is presented schematically in Fig. 1. Suppose that a maximum of three synchronized optical packets arrive simultaneously at the packet switch, and assume that the priority of the packet to pass the node decreases from Packet 1 to Packet 3. That is, Packet 1 has the highest priority and Packet 3 has the lowest priority. It should be noted that synchronization of the packets is required for the buffer to operate properly. The routing of Packet 1 and Packet 2 is shown in [4]. An optical threshold function that is driven by Packet 1 controls a wavelength routing switch, so that (in the presence of Packet 1) Packet 2 is delayed for one packet period [4]. Similarly, the routing of Packet 3 is determined by the presence of Packet 1 and Packet 2. An optical arbiter that drives a wavelength routing switch is employed to decide whether packet contention takes place. The wavelength routing switch is operated by wavelength conversion in combination with a demultiplexer. We use a winner-take-all LNN as an optical arbiter, which is suitable for all-optical processing of telecommunication data [5], [6]. Since wavelength conversion requires continuous-wave (CW) light to be injected into the wavelength converter simultaneously with the data packet, the first function of the LNN is to generate CW light at a specific wavelength. Table I shows the truth table of the LNN that acts as an optical arbiter. The wavelength of the CW output of the LNN controls the wavelength routing switch, and thus the buffer output.

First, assume that only Packet 3 arrives at the buffer and that Packet 1 and Packet 2 are absent. Thus, no packets are input to the LNN (see Fig. 1). It follows from Table I that the LNN should be trained in such a way that CW light at wavelength λ_1 outputs from the arbiter. Therefore, the wavelength of Packet 3 is converted to λ_1, and Packet 3 is routed into Port 1, passing the buffer without any delay (see Fig. 1).

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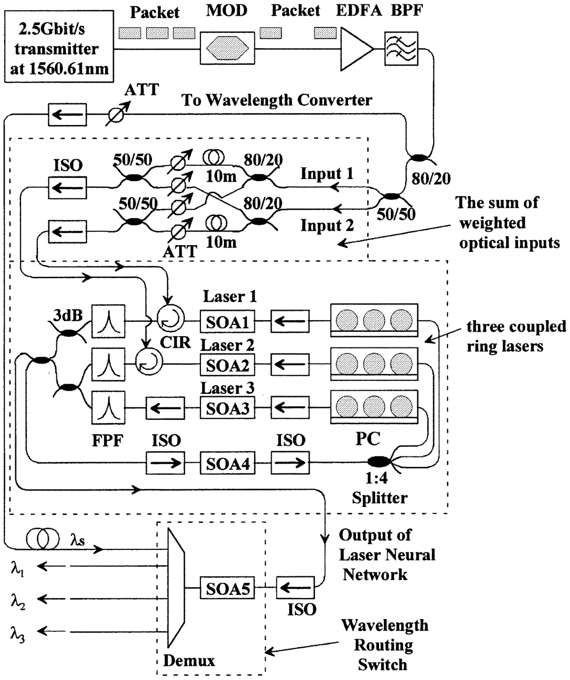


Fig. 2. Experimental setup of an LNN that can be used as an all-optical arbiter. ATT: variable optical attenuator. FPF: Fabry–Pérot filters. ISO: isolator. CIR: circulator. Demux: demultiplexer.

In the second case, only one data packet (either Packet 1 or Packet 2) is input to the LNN. Crucial in our buffering concept is that the LNN can be trained in such a way that the output state only depends on the number of packets that are input to the LNN and not on the specific input ports [6]. According to Table I, the LNN has to output CW light at wavelength λ_2, if only one packet is injected. Hence, Packet 3 is routed into Port 2, undergoing one packet period of delay.

Finally, both Packet 1 and Packet 2 arrive simultaneously at the LNN. In this case, the LNN has to output CW light at wavelength λ_3 (see Table I). Hence, Packet 3 is routed into Port 3, undergoing two packet periods of delay. Below we describe an LNN that has the functions described above, and we show that the concept can be used for buffering of telecommunication date packets.

III. EXPERIMENTS

The experimental realization of an LNN with the properties that are described above is presented schematically in Fig. 2. The LNN that acts as the optical arbiter is depicted in the two upper dashed box of Fig. 2. The LNN is made out of two parts [6]. In the first part, the optical inputs are weighted. The weighting of the LNN inputs is carried out by a system of variable optical attenuators and couplers. The second part of the LNN consists of three coupled ring lasers, in which semiconductor optical amplifiers (SOAs) act as the laser gain media. The wavelengths are selected by Fabry–Pérot filters. Optical isolators are used to allow the light to travel in only one direction, thus ensuring lasing in one direction. External light is injected into the coupled laser cavities through this system of input weights. The choices of the input weights determine the truth table of the LNN, i.e., different weights lead to different logic operations. The weights can be determined by using the stochastic learning algorithm of [6], [7], so that in each state, only one laser is lasing while the other lasers are suppressed. Our LNN consists of three coupled ring lasers and has three states. In State 1, light from Laser 1 suppresses lasing in the Laser 2 and Laser 3, thus Laser 1 is dominant. In State 2, Laser 2 is dominant and suppresses lasing in the other two lasers, and in State 3, only laser 3 is lasing and suppresses Laser 1 and Laser 2. Laser 1 has the highest output power and suppresses lasing in other two. Thus, if no external light is injected, the system is in State 1. Injection of external light changes the states of the arbiter.

In the experimental setup, a laser and an external modulator (MOD) are used to generate optical packets. The laser has a coherence length of several meters and the wavelength is 1560.61 nm. The bit rate of the packets is 2.5 Gb/s, and the bit patterns in the packets have a nonreturn-to-zero data format and form a $2^{15} - 1$ pseudorandom binary sequence. The packets are then amplified by an erbium-doped fiber amplifier and subsequently filtered by a tunable bandpass filter (BPF) with 3-nm bandwidth. An optical splitter is used to split the optical power of the packet into two parts. The first part, representing Packet 3 in Fig. 1, is fed directly into the wavelength converter. The second part is first split by a 3-dB coupler, representing Packet 1 and Packet 2, respectively (see Fig. 1). Packet 1 and Packet 2 enter the LNN, and are then weighted. The light that is injected into the LNN through Input 1 and Input 2, is decorrelated by using two optical fibers of 10 m each. However, in a realistic situation, the 10 m of fiber are redundant because the congested packets are not coherent. The weights are determined by the coupler ratios and the amount of attenuation in the variable attenuators. The weighted inputs are coupled into the coupled laser cavities via circulators. The external optical power injected into Laser 1 via the circulator is higher than the optical power injected into Laser 2, so asymmetric couplers (80/20) are used in the experiment. Polarization controllers (PCs) are used to correct for polarization changes in the connecting fiber. SOA 4 is used to increase the output power of the arbiter. The relative output powers of the coupled ring lasers are controlled by the injection current of each SOA (SOA 1 to SOA 4). The output of the LNN is fed into SOA 5, which acts as a wavelength converter operated by cross-gain modulation. The demultiplexer spatially directs the packet into a specific port based on the wavelength of the packet.

In the first experiment, we demonstrate the static operation of the arbiter. The wavelength of the three lasers are $\lambda_1 = 1549.32$ nm, $\lambda_2 = 1550.92$ nm, and $\lambda_3 = 1552.52$ nm. The spectral output of the LNN is presented for different inputs in Fig. 3. It follows from Fig. 3(a) that Laser 1 (1549.32 nm) is dominant if no external light is injected. In Fig. 3(b) and (c) the spectrum of the arbiter is shown if 8.2 dBm of external light is injected either at Input 1 or at Input 2. It can be seen that Laser 2 (1550.92 nm) is dominant if external light is injected at one of the two input ports. Finally, Fig. 3(d) shows the spectrum if 8.2 dBm of external light is injected in Input 1 and Input 2, simultaneously. In this case, only Laser 3 is lasing, at a wavelength of 1552.52 nm. It is shown in Fig. 3 that the truth table of Table I, which is required for buffering purpose, is indeed realized. The contrast ratio among the different states in the LNN is over 30 dB. Moreover, an eye diagram after the wavelength

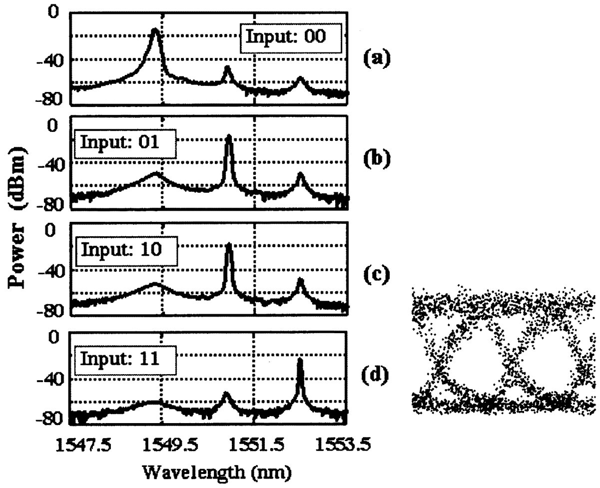
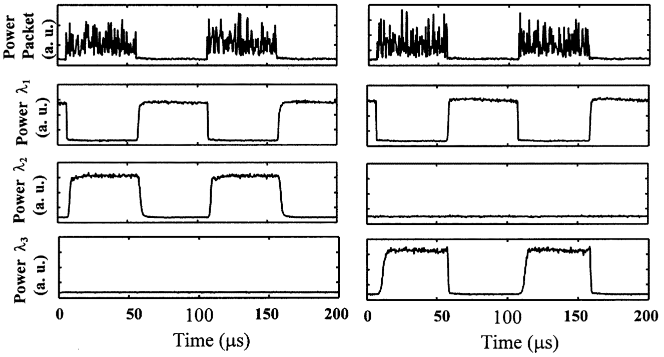


Fig. 3. The measured spectral output of the LNN for different input cases, as well as an eye diagram of the converted output data when the input case is "11." The input case is related to truth table in Fig. 1. For instance, the Input case "10" represents that Packet 1 is present while Packet 2 is absent.



(a) (b)

Fig. 4. Dynamic output of LNN with and without the presence of injected packets at the input for (a) the "10" input case and (b) the "11" input case. The upper panel shows the external optical packet. The middle and lower panel are the dynamic output of LNN at each wavelength.

conversion at output λ_3 is presented in Fig. 3. The open eye indicates that the LNN output can be used to drive a wavelength routing switch so that error-free data transmission is possible.

In the second experiment the dynamic operation of the arbiter is demonstrated. First, an optical packet is injected into the arbiter via Input 1 while no packet is injected in Input 2 (this corresponds to the "10" case in Table I). If no external light is injected, Laser 1 is lasing while the others are suppressed. According to the results presented in Fig. 3, if external light is injected in one of the inputs, Laser 2 (1550.92 nm) becomes dominant. It can be observed from Fig. 4(a) that if an optical packet is injected in Input 1, Laser 1 switches OFF and Laser 2 switches ON. Laser 3 remains switched OFF. A similar result can be obtained if only light is injected in Input 2. As soon as injection of the packet is stopped, the arbiter switches back to its original state, outputting CW light at wavelength λ_1. The packets we used have duration of 50 μs. In Fig. 4(b), the dynamic operation is demonstrated if simultaneously optical packets are injected in Input 1 and Input 2 (this corresponds to the "11" case in Table I). According to Fig. 3, in this case, Laser 3 should switch ON. This is clearly visible in Fig. 4(b), where it can be observed that Laser 1 switches OFF and Laser 3 switches ON, as long as there is a packet injected at Input 1 and Input 2.

It is noted that the variability of the CW output power of the ring lasers leads to a variability in the packet output power. However, interferometric wavelength converters at the output of the buffer (not shown in this letter) can be used to reset the wavelength of the packet and to reshape the packet simultaneously [2]. Network architecture, in which this optical buffering concept is applied, is given in [2].

IV. CONCLUSION

We have proposed an all-optical buffering concept that can be used to resolve packet contention in the case that three synchronized packets arrive at an optical packet buffer. The crucial component in this concept is an all-optical arbiter that decides whether packet contention takes places and that drives a wavelength routing switch. We have employed an LNN as an optical arbiter. Experimental results indicate that an LNN made from three coupled lasers is suitable as an optical arbiter. The LNN shows a contrast ratio of more than 30 dB between the output states. Moreover, the LNN output is suitable for driving a wavelength converter switch. We obtained a clear open eye after wavelength conversion.

The packet length is determined by the particular implementation of the LNN used in the experiment. The lasers used to form the LNN were constructed from standard commercially available fiber pigtailed components. Therefore, the length of the laser cavities are several tens of meters. Thus, the component lasers had low intrinsic modulation bandwidths, which limited the speed. However, integrated versions of the LNN could attain speeds in the order of a gigahertz, indicating that the guardband between the packets could be reduced to several nanoseconds. In principle, the LNN can be extended further, so that it could be employed in a system that is capable of handling the contention of more than three packets. Our buffering concept can be employed in larger packet buffering systems to enlarge the buffer depth so that packet loss can be avoided [1], [2].

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