Investigation on performance of all optical buffer with large dynamical delay time based on cascaded double loop optical buffers*

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Optical buffers are critical for optical signal processing in future optical packet-switched networks. In this paper, a theoretical study as well as an experimental demonstration on a new optical buffer with large dynamical delay time is carried out based on cascaded double loop optical buffers (DLOBs). It is found that pulse distortion can be restrained by a negative optical control mode when the optical packet is in the loop. Noise analysis indicates that it is feasible to realise a large variable delay range by cascaded DLOBs. These conclusions are validated by the experiment system with 4-stage cascaded DLOBs. Both the theoretical simulations and the experimental results indicate that a large delay range of 1–9999 times the basic delay unit and a fine granularity of 25 ns can be achieved by the cascaded DLOBs. The performance of the cascaded DLOBs is suitable for the all optical networks.

Keywords: all optical packets switching, optical buffer with large delay range, signals impairment, noise analysis of semiconductor optical amplifier

PACC: 4280S, 4265, 4290

1. Introduction

All-optical packet switching (OPS), in which data packets are disposed, switched and transmitted in the optical domain, is regarded as an ultimate target for the optical networks. In OPS networks, optical buffers are required to temporarily store packets for synchronizing, resolving packet contention, disposing packet header or smoothing network traffic. Up to now, optical buffers have been generally implemented by using 'slow-light' technologies, such as electro-magnetically induced transparency, stimulate Brillouin scattering (SBS) and stimulate Raman scattering (SRS), or fibre delay line (FDL) technologies. Slow-light optical buffer appears to be very promising due to its compactness, large delay range and fine granularity, but some problems of many critical technologies need to be solved before their practical application, such as, tradeoff between the bandwidth and the storage time, method of optical power coupled with optical fibres, and the means of writing or reading operations. The most practical optical buffer technology for OPS applications is based on FDL combined with optical switches. Depending on the different topologies, the FDL-type optical buffers can be grouped into two categories: traveling-wave buffer and fibre-loop buffer. The traveling-wave buffer is usually bulky and thus not suitable to the full-size networks for collision avoidance because it generally consists of multiple optical fibres whose lengths are equivalent to multiples of the packet duration, and many optical switches to select particular delay time, while for fibre-loop buffer, the delay time is determined by the length of the loop and the circulation number, as its size is relatively compact and less components are occupied. Though the buffer size can be reduced greatly by wavelength switched packet network compared with the complementary metal–oxide–semiconductor random access memory (CMOS RAM), which can store a single bit in an area of less than 1 μm^2, either travel-

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ing buffer or fibre-loop buffer is space consumption, for one bit occupies approximately 5 mm of length on the optical fibre.[1] Moreover, in order to solve packet collision problem effectively, the optical buffer is expected to change its delay time dynamically in a large range and to be reconfigurable in several nanoseconds before the packet has already left from the buffer. Therefore the fundamental difficulty in challenging the designer of an optical buffer is that the variable delay time in a large range must be implemented with delay-lines fixed in length. To the traveling-wave buffer, cascaded switches fabric are used to select different lengths of FDLs to achieve various delays. In Ref. [2], a traveling-wave buffer was realised by cascading a large number of electronically controlled 2×2 switch modules with a moderate amount of buffering. In Ref. [3], Yeo *et al.* proposed a cascaded buffer with architecture similar to tree topology and a delay of 6.6 μs was demonstrated in an experimental system composed of two delay sections. However, some problems, such as the large insertion losses of the 2×2 couplers, input polarisation dependence, as well as low on-off speed of switches electronically controlled, need to be solved before it can be used in practice. In Ref. [4], Chi *et al.* proposed a multi-loop configuration based on an optical cross-point switch matrix. A more compact size and a finer granularity were achieved, but the drawbacks for this buffer were serious distortion in signal and high consumption in power due to active vertical couplers. Reference [5] presents a buffering structure by embedding 3^J feed-forward optical fibre delay lines into a re-circulating loop. Although a delay step as small as 0.5 ps with an accuracy of about 0.03 ps was realised by this hybrid buffer, amplified spontaneous emission (ASE) noise accumulated quickly as the packet traveled in the loop multiple times. As a result, the dynamical delay range was limited to a few circulations in all these optical buffers. In the present paper, we propose a new type of fibre-loop buffer design, which is based on the cascaded double loop optical buffers (DLOBs). This new decimal buffer is cost-effective, compact, easy to control, and can provide a fine delay granularity, an ultra-large and continuously variable delay time range, and a dynamic reconfiguration in several nanoseconds.

2. Principle

The particular implementation of the proposed buffer structure is shown in Fig. 1, where several DLOBs are connected in series with each other to form a cascaded structure.

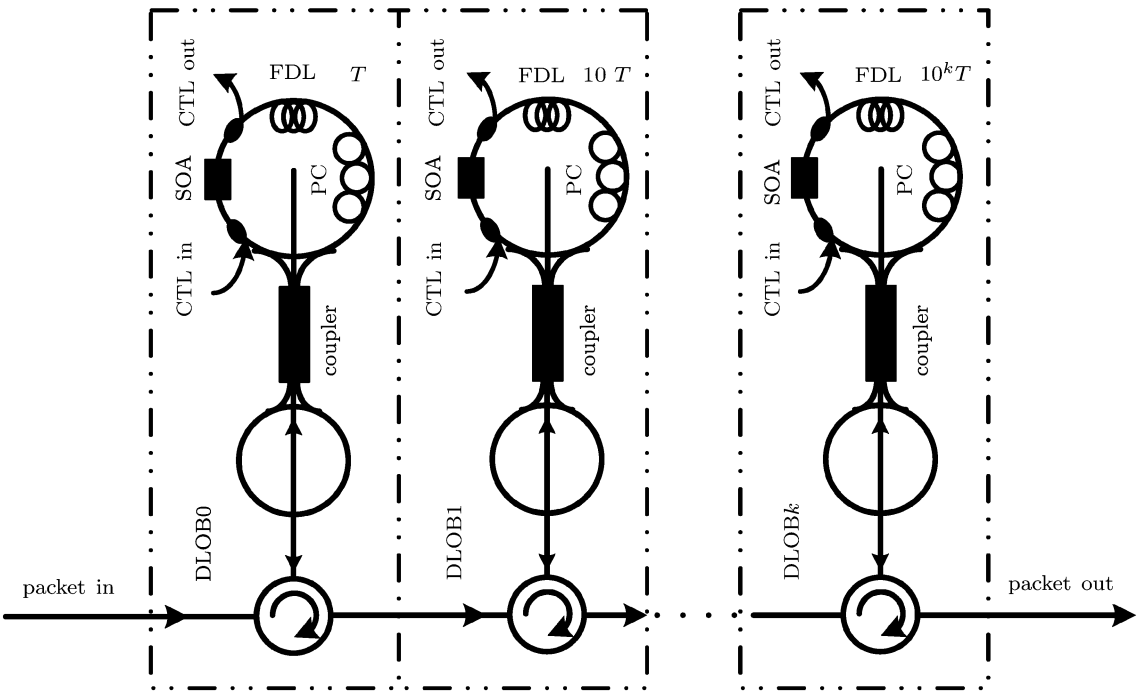


Fig. 1. Structure of cascaded DLOBs.

The delays after a round-way trip of the packets in DLOB0, DLOB1... DLOBk are T, $10T$, ..., 10^kT, respectively. Assuming that the numbers of the cycles in their corresponding DLOBs are n_0, n_1, ..., n_k respectively, the total delay $t_{\rm d}$ can be given by

$$t_{\rm d} = n_0T + 10n_1T + \ldots + 10^k n_kT. \tag{1}$$

If the numbers $n_0 \sim n_k$ are controlled to change from 0 to 9, a decimal optical buffer is achieved.

In this new configuration, DLOB is a basic buffer unit. So we must analyse its storing principle simply. The structure of DLOB (shown in Fig. 2) is based on collinear 3×3 fibre coupler,[6] with branches 1 and 3 connected forming the left loop and branches 4 and 6 connected forming the right loop, combined with semiconductor optical amplifier (SOA) into a nonlinear element. The input packets enter the buffer from the port C1 of the circulator. They undergo multiple-cycle delay or no delay, depending on the phase difference $\Delta\varphi$ between the optical signals propagating along the two branches of 3×3 coupler. $\Delta\varphi$ is described by[7]

$$\Delta\varphi = \varphi_{\rm CW} - \varphi_{\rm CCW} = -\frac{\alpha}{2}\ln\frac{G_{\rm CW}}{G_{\rm CCW}}, \tag{2}$$

where $\varphi_{\rm CW}$ and $\varphi_{\rm CCW}$ are the phases of data packets in the clockwise (CW) and counter-clockwise (CCW) directions respectively, $G_{\rm CW}$and $G_{\rm CCW}$ are the gains of signal light in the CW direction and CCW direction respectively, and α is the line width enhancement factor. When $\Delta\varphi$ equals π, a reading or writing operation can be executed. According to Eq. (1), the buffer can be controlled by injecting control light beams with different powers when the packets pass through SOA in CW or CCW direction.

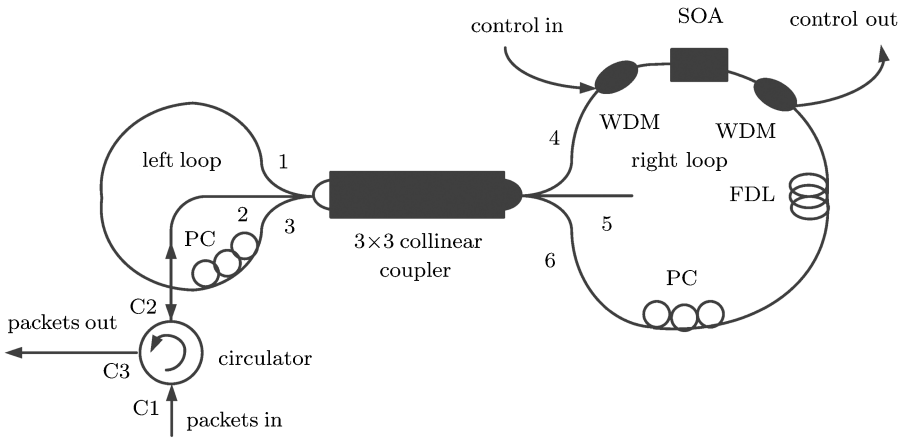


Fig. 2. Schematic diagram of DLOB.

Although DLOB has several advantages such as compactness, high switch speed (< 0.8 ns) and simple operation, the number of cycles of data packet in the single DLOB is no more than 20.[6,8,9] In order to implement a larger dynamic adjustable delay by cascaded DLOBs, a feasible measure must be found to improve the number of cycles of data packet in the loop. As in the fibre-loop optical buffer, the packets are required to pass through the SOA many times, the signal impairment due to the nonlinear effects of SOA, such as cross-gain modulation (XGM) and cross-phase modulation (XPM), cannot be neglected. When the group-velocity dispersion is taken into account, the equation describing the propagation of an optical pulse in the SOA can be obtained as[10]

$$\begin{aligned}\frac{\partial A(z,\tau)}{\partial\tau} - \frac{\rm j}{2}\beta_2\frac{\partial^2 A(z,\tau)}{\partial\tau^2} &= \frac{1}{2}\frac{g-\varepsilon_2P^2}{1+\varepsilon_1P} - \frac{\rm j}{2}\left[\alpha_{\rm N}g - \alpha_T\frac{\varepsilon_1gP+\varepsilon_2P^2}{1+\varepsilon_1P}A(z,\tau)\right] \\ &\quad -\left(\Gamma_2\gamma + {\rm j}\Gamma_2'\frac{\omega_0}{c}n_2\right)\frac{1}{\sigma}PA(z,\tau) - \frac{1}{2}a_{\rm int}A(z,\tau),\end{aligned} \tag{3}$$

where $A(z,\tau)$ is the slowly varying envelope of the optical pulse in units of (watts)$^{1/2}$, β_2 is the second-order group dispersion coefficient, σ is the mode cross section (= wd/Γ), Γ is the traditional confinement factor, w and d are the width and the thickness of the active layer, ε_1 is the nonlinear gain compression factor for carrier

heating and spectral hole burning, ε_2 is the nonlinear gain compression factor for two-photon absorption (TPA), $\alpha_{\rm N}$ is the traditional linewidth enhancement factor, α_T is the temperature linewidth enhancement factor, Γ_2 is the confinement factor for TPA, Γ_2' is the confinement factor for nonlinear refraction, γ is the coefficient of TPA, n_2 is the nonlinear gain refractive index, ω_0 is the photon angular frequency, $a_{\rm int}$ is the internal loss, c is the velocity of light, and g is the gain coefficient and can be expressed as[10]

$$\frac{\partial g}{\partial \tau} = \frac{g_0 - g}{\tau_{\rm c}} - \frac{1}{E_{\rm s}} \frac{g - \varepsilon_2 P^2}{1 + \varepsilon_1 P} P + \Gamma_2 \gamma' P^2, \qquad (4)$$

with $\tau_{\rm c}$ being the carrier lifetime, g_0 the small signal gain, $\gamma' = \alpha_{\rm N}\beta_2/h\nu\sigma^2$, $E_{\rm s} = \tau_{\rm c}P_{\rm s}$, $P_{\rm s}$ the saturation power of SOA. Equations 2 and 3 indicate that some changes in pulse shape will be present while the pulse is passing through SOA. The shape changes result in a pattern distortion which restricts the increase of the buffered cycles. In Ref. [11], a control method of injecting a negative optical pulse into SOA is presented to increase the buffered cycles. When the negative optical pulse control mode is used, the output pulse distortion can be evaluated from Eqs. (2) and (3). In practice, the input packet pulse may not be an ideal square shape. Therefore, the signal powers of the leading edge and the trailing edge of the input packet may be less than the power of midpoint of the input packet. It is obviously that the power of the optical control pulse, which is required to be able to cover the leading and trailing edges of the input packet, should be less than the power in the midpoint. But the power of the optical control pulse is fixed for the whole packet duration, the different parts of the input optical pulse will experience different gains and different phase shifts. Even if the shape of the input packet signal is an ideal square pulse, the gain in leading edges is bigger than those of the other parts when the gain restoring time is considered, therefore pulse distortion also appears. If a 'base' auxiliary light with high power is introduced into SOA, the SOA is saturated. When the different parts of the optical pulse pass by the saturated SOA, the fluctuation of carrier density in the active region is negligible. The pulse distortion will be restrained. The input packet pulse is assumed to have a Gaussian or super-Gaussian shape as

$$P(T) = P_0 \exp\left[-\left(\frac{T}{T_0} \right)^{2m} \right], \quad m = 1, 2, 3 \ldots, \qquad (5)$$

where T is measured in a frame of reference moving with the pulse at the group velocity $v_{\rm g}$ ($T = t - z/v_{\rm g}$), T_0 is the half-width at the $1/e$-folding point of the intensity profile, the parameter m controls the degree of edge sharpness, and P_0 is a constant. From Eqs.(1)–(4), the shapes of input pulse and output pulse after being stored in the buffer for 60 cycles can be achieved and are shown in Fig. 3. It is interesting to find that the output pulse has a smaller distortion after being buffered 60 cycles when the negative optical control is employed, with an auxiliary light, with a power as high as 4 mW injected into the SOA. Although the distortion effect will be intensified when the input pulse shape is closer to the square pulse shape (with a larger value of m), the shape distortion would not disturb the identification of the output pulse. In Ref. [12], the shape distortion in the process of reading or writing operation was discussed, but the change of carrier density could not be taken into account and so the results could not depict the shape of output pulse. In wavelength conversion or optical logic gate, pattern distortion was clear when a continuous bit stream was injected into SOA.[13] In the application of optical switch through using a negative pulse control mode with an injection of auxiliary high-power light, the pattern distortion is also negligible.

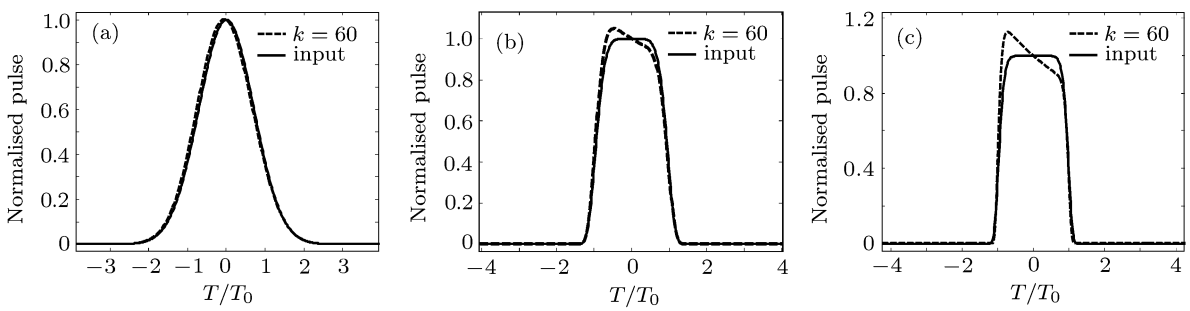


Fig. 3. Pulse distortions after being buffered 60 cycles with Gaussian and super-Gaussian pulses for three different values of m: $m = 1$ (a), 3 (b), and 5 (c).

In a common optical fibre transmission system, pulse is widened due to the fact that the fibre dispersion is the main reason of the signal impairment. In DLOBs, when the total length of fibre which the packet travels exceeds a certain value, the effects of nonlinearity of SOA and fibre dispersion should be considered simultaneously. A comprehensive simulation result is shown in Fig. 4 when the length of loop for the DLOB is 2000 m and the bit rate of input packet is 2.488 Gbit/s. It is obvious that the bottom of the pulse is widened and the top of pulse is narrowed after the packet is buffered 60 cycles in the DLOB. The shape of the output pulse is slightly deteriorated and would not disturb the receiver to the extent of undistinguishing the correct results in this case. However, with the increase of the total fibre length or the signal bit rate, the scheme of dispersion compensation must be adopted.

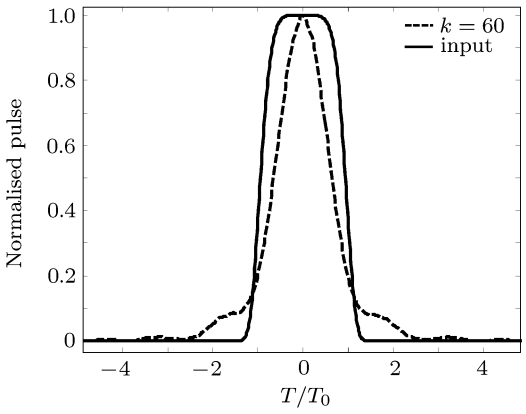


Fig. 4. Pulse distortion in the dispersion system.

From the discussion on the shape distortion of output pulse, it is possible to realise a large dynamical delay range by the cascaded DLOBs with the control method of negative optical pulses. The shape distortion is not the only factor of the signal impairment. When the packets pass through the SOA many times, the signal-to-noise ratio (SNR) of output signal will degrade because of the accumulation of ASE noises. In order to quantitatively describe the noise characteristics, the process of the packets in DLOB can be simplified by an SOA repeating system (shown in Fig. 5) because of the injections of auxiliary light with high power. During reading or writing, the gain $G_{\rm r}$ or $G_{\rm w}$ is dependent on the power of control optical pulse and approximately equal to a constant G'. Adjusting variable optical attenuator (VOA) allows the SOA to keep a constant gain $G_{\rm i}$. The incident light is assumed to be coherent. The mean value and the variance value of the signals written into the loop can be expressed as[14]

$$\langle n_0\rangle = G'L'\langle n_{\rm in}\rangle + (G'-1)n_{\rm sp}\Delta f, \tag{6}$$

$$\begin{aligned}\sigma_0^2 \;=\; & G'L'\langle n_{\rm in}\rangle + (G'-1)n_{\rm sp}\Delta f \\ & +2G'L'(G'-1)n_{\rm sp}\langle n_{\rm in}\rangle + (G'-1)^2 n_{\rm sp}^2\Delta f,\end{aligned} \tag{7}$$

where $\langle n_{\rm in}\rangle$ is the mean value of the photon number incident on the SOA, Δf is the bandwidth of the filter, $n_{\rm sp}$ is the population of the inversion parameter of the amplifying medium, L is the insertion loss in the loop, and L' is the loss from C1 or C2 port of the circulator to the SOA.

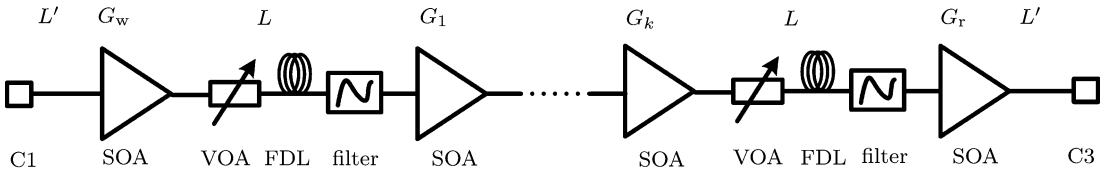


Fig. 5. Equivalent structure for single DLOB.

According to the analysis method similar to that in Ref. [15], the relations between SNR and the storage cycle k are obtained in single DLOB and cascaded DLOB respectively and shown in Fig. 6. Curve 1 reflects the relation between SNR and the storage cycle k in single DLOB. It is clear that SNR is less than 5 dB while the number of the storing circles in the DLOB is 36, therefore, it is difficult for 4-stage cascaded buffers to realise a dynamical delay range of 1–9999 times the basic delay unit. However, the process that packet experiences in a single DLOB is different from the one in cascaded DLOBs. Reading and writing operations are

required for each storage unit of the proposed buffer configuration. The amplitude of the packets is amplified when they are read or written with the negative optical pulse control mode. Curve 2 represents SNR for cascaded DLOBs. The simulation result indicates SNR is enhanced by 7 dB after the packets buffered 9 cycles in DLOB0–DLOB3 respectively. In our experiments, if the parameters, such as the power of control optical pulse, the current injected into the SOA, and the power losses, are optimized in each storage unit, the final SNR can reach up to 19 dB.

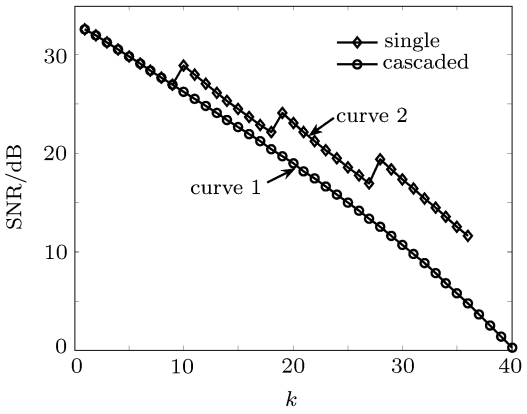


Fig. 6. SNR vs. buffered cycles.

From the analyses of the shape distortion and SNR, we find that the optical buffer with a large dynamical delay range can be fulfilled by cascaded DLOBs. The delay variation range of 1–9999T is possible to be realised by 4-stage cascaded DLOBs. The length of the smallest loop is determined to be 5 m that is limited by the fibre length of the polarisation controller (PC) used in the experimental setup, hence the delay resolution is 25 ns. If the insertion loss can be reduced to 1.6–2 dB and a piezoelectric PC is employed,[16] the length of the smallest loop can be decrease to 1 m and the length of the largest loop can be increased to 10000 m. The delay time can be varied from 0 to 0.5 ms in steps of 5 ns. Thus fine granularity and the large variable delay can be achieved simultaneously in the cascaded DLOBs.

3. Experiment and discussion

The experimental setup is shown in Fig. 7. The lengths of the FDLs in DLOB0, BLOB1, DLOB2 and DLOB3 are about 5, 48, 530 and 4800 m respectively. So the $t_{\rm d}$ can be programmed in a range from about 0 to 0.2457 ms, and the adjustable resolution is 25 ns. A continuous-wave light from a distributed-feedback (DFB) laser ($\lambda_{\rm s} = 1556.56$ nm) is modulated by a $LiNbO_3$ modulator driven by a 2.488 Gbit/s sequence from a pulse pattern generator (PPG). The currents injected into the four SOAs are 205, 210, 210, and 215 mA, respectively. Four DFB lasers ($\lambda_{\rm c} = 1553.8$ nm) are used to generate synchronizing control pulses. The output of the buffer is detected by a photodetector and monitored by an OSC.

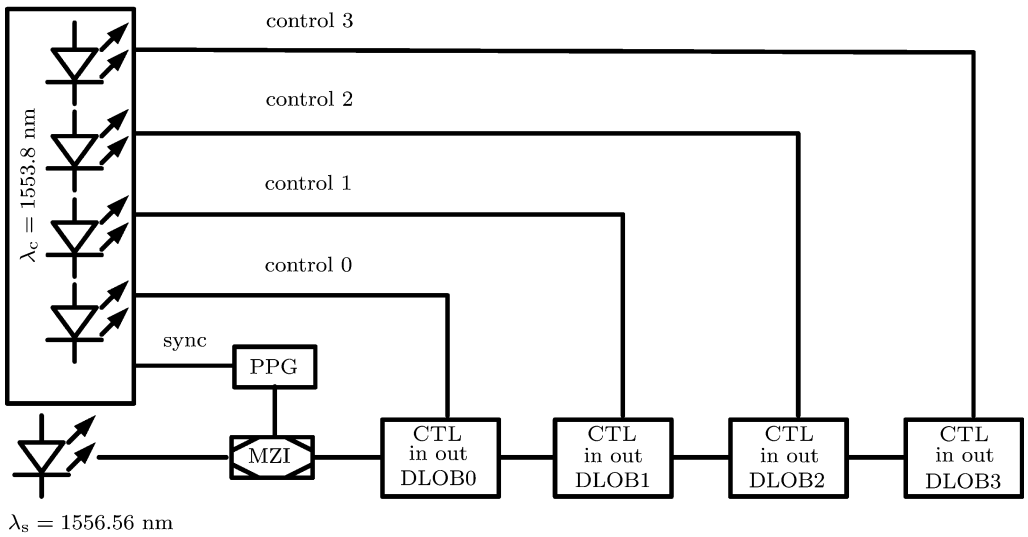


Fig. 7. Experiment system.

The data packet consists of a header and a payload. Generally, the header includes some control messages,

such as the source address, the destination address, the length of packet, the service quality and so on. The header is not stored in cascaded DLOBs, but it is separated from the payload and sent to the header processor. In our experiment, the control function of the header is simplified and the header is regarded only as the reference of the delay time of the payload. The header is 5555 h while the payload is E113 h. The packet is repeated every 0.5 ms. The results recorded by the OSC are shown in Fig. 8. The pulse shape almost has no change at all after the payload has stored 9 cycles in DLOB0 (Fig. 8(a)). The peak power of the signal is a bit more than 600 μW, while the noise amplitude peak is less than 15 μW. The leading edge of the pulse becomes somewhat abrupt, and the noise power increases to 20 μW when the packet has finished 9 round-trips in DLOB1 (Fig. 8(b)). After travelling 9 cycles in DLOB2, the leading edge is more abrupt and the noise power is approximately 25 μW (Fig. 8(c)). After another 9 loops in DLOB4, the bottom of output pulse is widened and the top of the output pulse is narrowed due to fibre dispersion and nonlinear effects of the SOA (Fig. 8(d)). The noise power is about 30 μW, and SNR is about 13dB. These results are in agreement with the theoretical analyses.

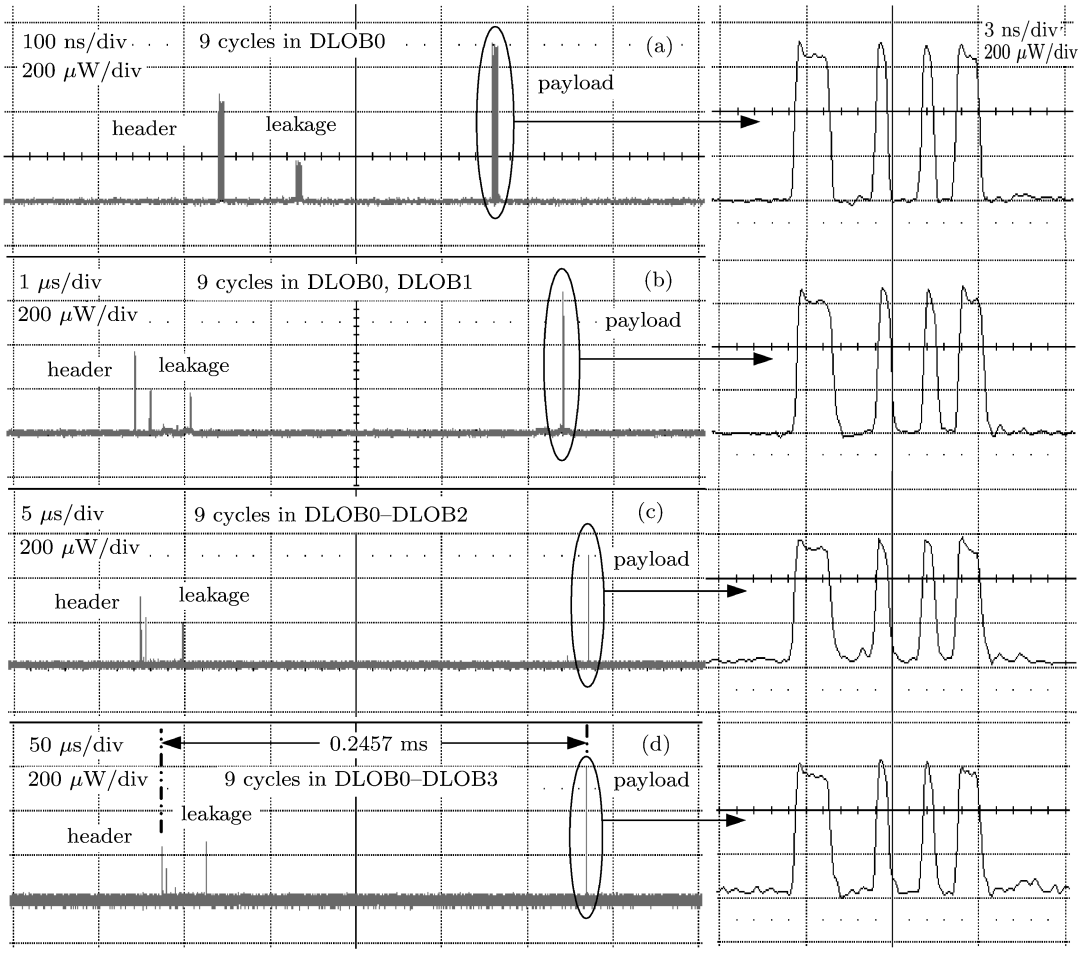


Fig. 8. Output waveforms and their details in time domain.

The eye diagram cannot be recorded because the packet is too short. In order to evaluate signal quality of the cascaded DLOBs, we also record the eye diagram of output signal by using a long packet. The packet includes 200 bits, repeats every 0.5 ms, and is input from DLOB1 and output from DLOB3. The experimental results are shown in Fig. 9. After being buffered in a 3-stage DLOB, the shape of waveform is perfect and eye diagram is clear and open, which allows error-free operation.

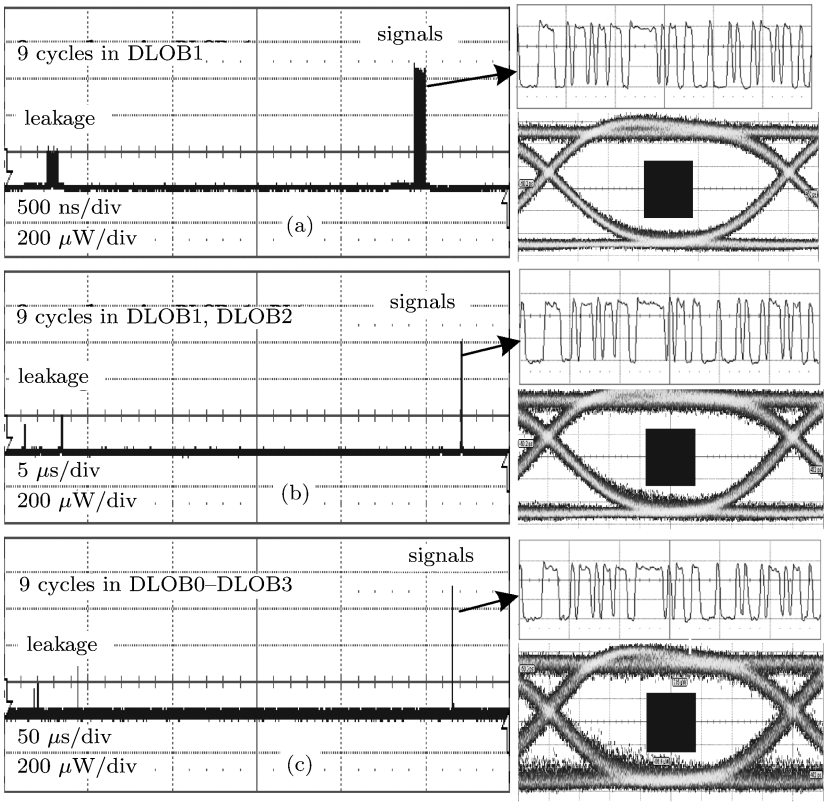


Fig. 9. Output waveforms and their eye diagrams.

4. Conclusion

DLOBs are compact, simple, easy to operate and cost-effective. By using a negative pulse control mode with an injection of auxiliary high-power light, the shape distortion of the optical pulse can be restrained. A new optical buffer, the cascaded DLOBs with a large dynamical delay range, is proposed and demonstrated experimentally. A delay range of 1–9999 times the basic delay unit and a fine granularity of 25 ns can be achieved in the same time with the new cascaded DLOBs. Experiments and simulations indicate that SNR is enhanced by 7 dB and the shape distortion can be neglected when the packet is stored for 0.2457 ms in the cascaded DLOBs. The performance of the cascaded DLOBs is suitable for the all optical networks.

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