different 6.3 Gbit/s channels are clearly observed. The BER performance of the six channels is shown in Fig. 5. Note that the average received optical power is that of the 100 Gbit/s signal monitored right after the optical attenuator (see Fig. 2), corresponding to the receiver sensitivity for the 100 Gbit/s signal. The baseline 6.3 Gbit/s BER curve was measured at 1555 nm at the output from the intensity modulator. Fig. 5 shows that simultaneous demultiplexing of the six channels is successfully performed with no error floor. The power penalties range from 3.0 (channel 3) to 5.5 dB (channel 1), taking into consideration the subtraction of 12 dB, i.e. the OTDM multiplication factor of 16. Fig. 6 shows the characteristics of demultiplexed channel 1 with the wavelength of 1535 nm, including the streak camera image (Fig. 6*a*), the eye-diagram observed after the O/E-converter with 6 GHz bandwidth (Fig. 6*b*), and the output of the electrical decision circuit (Fig. 6*c*). The demultiplexed signal has a clear eye-opening. The uplift of the 'space' level comes from the spectral power component of the original down-chirped clock at the corresponding wavelength, which simply results in an increase in the decision level.

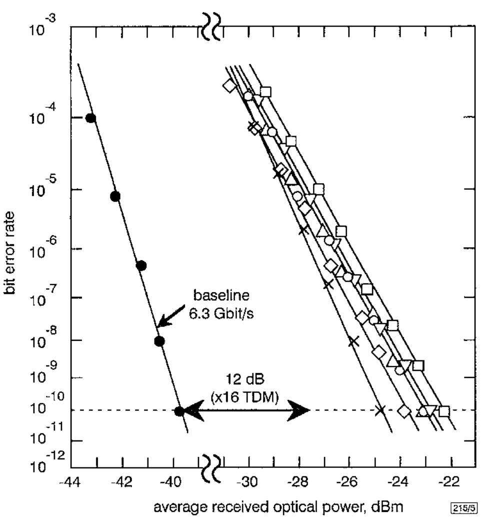

Fig. 5 *Bit error rate performance, PRBS $2^{15}-1$*

□ ch1, ○ ch2, × ch 3, △ ch 4, ◇ ch 5, ▽ ch 6

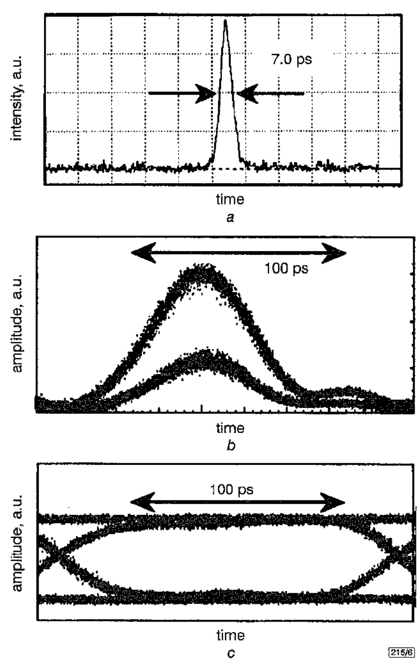

Fig. 6 *Characteristics of demultiplexed Ch. 1*

a For streak camera image, *b* For eye-diagram
c For output of decision circuit

Conclusion: We have proposed a novel multiple-channel output all-optical OTDM demultiplexer utilising cross-phase modulation (XPM)-induced chirp compensation (MOXIC). Stable, error-free, simultaneous six-channel-output, 100 to 6.3 Gbit/s demultiplexing has been successfully demonstrated by the MOXIC. The MOXIC does not utilise any parametric process-based wavelength conversion or interferometric switching technique, and, consequently, it has a very simple setup with both low insertion loss and stable operation. It may offer a practical solution to all-optical time-division demultiplexers over 100 Gbit/s.

Acknowledgment: The authors would like to thank Y. Yamabayashi for fruitful discussions, to I. Yamashita and I. Kobayashi for making this work possible.

5 January 1997
Electronics Letters Online No: 19980399

K. Uchiyama, S. Kawanishi and M. Saruwatari (*NTT Optical Network Systems Laboratories, 1-1 Hikarinooka, Yokosuka, Kanagawa, 239 Japan*)

References

1 KAWANISHI, S.: 'Ultrahigh-speed optical time-division-multiplexed transmission technology based on optical signal processing', to be published in *IEEE J. Quantum Electron.*

2 MORIOKA, T., MORI, K., and SARUWATARI, M.: 'Ultrafast polarisation-independent optical demultiplexer using optical carrier frequency shift through crossphase modulation', *Electron. Lett.*, 1992, **28**, pp. 1070–1071

3 MORIOKA, T., KAWANISHI, S., TAKARA, H., and SARUWATARI, M.: 'Multiple-output, 100 Gbit/s all-optical demultiplexer based on multichannel four-wave mixing pumped by a linearly-chirped square pulse', *Electron. Lett.*, 1994, **30**, pp. 1959–1960

4 UCHIYAMA, K., KAWANISHI, S., and SARUWATARI, M.: '100 Gbit/s multiple-channel output all-optical OTDM demultiplexing using multi-channel four-wave mixing in a semiconductor optical amplifier', to be published in *IEEE Photonics Technol. Lett.*

5 UCHIYAMA, K., TAKARA, H., MORIOKA, T., KAWANISHI, S., and SARUWATARI, M.: '100 Gbit/s multiple-channel output all-optical demultiplexing based on TDM-WDM conversion in a nonlinear optical loop mirror', *Electron. Lett.*, 1996, **32**, pp. 1989–1991

6 TAKARA, H., KAWANISHI, S., and SARUWATARI, M.: 'Stabilisation of a modelocked Er-doped fibre laser by suppressing the relaxation oscillation frequency component', *Electron. Lett.*, 1995, **31**, pp. 292–293

7 MORI, K., TAKARA, H., KAWANISHI, S., SARUWATARI, M., and MORIOKA, T.: 'Flatly broadened supercontinuum spectrum generated in a dispersion-decreasing fibre with convex dispersion profile', *Electron. Lett.*, 1997, **33**, pp. 1806–1808

8 YAMADA, M., ONO, H., KANAMORI, T., SAKAMOTO, T., OHISHI, Y., and SUDO, S.: 'A low-noise and gain-flattened amplifier composed of a silica-based and a fluoride-based Er^{3+}-doped fiber amplifier in a cascade configuration', *IEEE Photonics Technol. Lett.*, 1996, **8**, pp. 620–622

On the odd-even ATM switch

C. Kolias and L. Kleinrock

The authors address some issues with respect to their previously proposed switching architecture the odd-even ATM switch.

System description: We would like to indicate that the work in [1] was anticipated by ours in 1995 and 1996 [3 – 5].

In particular, in [4] we describe the novel idea of an ATM switch where a single input queue is expanded into two separate FIFO queues each able to store incoming cells according to their desired output port. More specifically we let cells that are destined to the even-numbered output ports (i.e. 2, 4, 6, ...) join what we call the even queue while those destined to the odd-numbered output ports (i.e. 1, 3, 5, ...) join, respectively, the odd queue. This type of switching architecture was originally introduced to us by L.G. Roberts and we named it the odd-even ATM switch. The idea of the odd-even switch was first presented in [3]. In [5] we give an approximate throughput analysis of the odd-even model.

We here reproduce some of the key elements and issues of our previously published work on the subject of the odd-even ATM switch [Note 1].

Note 1: Parts of the following text contain a verbatim passage from our papers [4, 5].

Maximum throughput analysis: The arbitration policy in the odd-even switch takes place in two consecutive rounds per timeslot. In one round the even queues are arbitrated first while in the next one only those odd queues, whose corresponding even queues did not transmit a cell, are allowed to participate. In this way an input port always has the chance to transmit a cell from either an even or an odd queue, but not from both, within the same timeslot. For fairness we allow the order in which even and odd queues are polled to interchange in every timeslot. However, because the analysis of the odd-even model under this type of arbitration policy is intractable we modify the arbitration discipline as follows: we require that in every timeslot even queues are polled first. We expect that throughput will not be affected considerably as compared to the original model since unclaimed output ports (i.e. odd-numbered) will still have the chance to serve head-of-line (HOL) cells routed from their corresponding (odd) queues. For our analysis we make the simplified assumption of Bernoulli arrivals at the inputs (at rate λ) while output ports are uniformly distributed among the incoming cells. The switch has N inputs and N outputs.

We are interested in finding the saturation throughputs of the odd and even output ports, which we denote $\gamma_{E,max}$ and $\gamma_{O,max}$, respectively. We first derive an exact expression for $\gamma_{E,max}$ and then approximate $\gamma_{O,max}$, where, as we will see, the latter actually depends on $\gamma_{E,max}$. Our approach is similar to that described in [2]. Let N_j^E be the number of even HOL cells destined for output j. At steady state:

$$\gamma_E = \lambda_E = \frac{2}{N} \sum_{j \text{ is even}} E[\epsilon(N_j^E)] = E[\epsilon(N_j^E)] \quad (1)$$

where $\lambda_E/2$ is the arrival rate to the even queues and $\epsilon(x)$ is an indicator function ($\epsilon(x) = 0$ if $x \le 0$, $\epsilon(x) = 1$ if $x > 0$). Note that the even HOL cells are switched from any of the N (even) input queues to any of $N/2$ even output ports. Let also N_b^E denote the total number of HOL cells blocked (i.e. lost the contention) at the even queues after the first contention round. Then:

$$N_b^E = \sum_{j \text{ is even}} N_j^E - \sum_{j \text{ is even}} \epsilon(N_j^E) \quad (2)$$

Taking expectations in eqn. 2 and combining it with eqn. 1, we obtain, by symmetry:

$$\lambda_E = \gamma_E = E[N_j^E] - \frac{2E[N_b^E]}{N} \quad (3)$$

Let ρ_E be the steady-state probability that a cell moves into the HOL position of an even queue given that this position is free and M_E denote the number of released even HOL positions, clearly: $M_E = N - N_b^E$. This last equation combined with the flow conservation relationship describing the system for the even queues, $E[M_E]\rho_E = (N/2)\lambda_E = N\lambda_E/2$, gives

$$\frac{E[N_b^E]}{N} = 1 - \frac{\lambda_E}{2\rho_E} \quad (4)$$

As in [2] we further obtain

$$E[N_j^E] = E[A_j^E] + \frac{E[A_j^E(A_j^E - 1)]}{2(1 - E[A_j^E])} \quad (5)$$

where A_j^E is the number of new HOL cells destined for output j. In determining $E[A_j^E(A_j^E-1)]$, we find (cf. [5]) that A_j^E becomes Poisson(λ_E) as $N \to \infty$. Thus eqn. 5 gives

$$E[N_j^E] = \lambda_E + \frac{\lambda_E^2}{2(1 - \lambda_E)} \quad (6)$$

Applying Eqns. 4 and 6 in eqn. 3 we obtain $(2-\rho_E)\lambda_E^2 - 2(2\rho_E+1)\lambda_E + 4\rho_E = 0$. Solving this equation for λ_E when $\rho_E = 1$ gives the maximum achievable, by the even outputs, throughput: $\gamma_{E,max} = 3 - \sqrt{5} \simeq 0.764$.

It now remains to obtain the throughput of the odd output ports. Because not all the input ports (their odd queues) are available for the second contention round it is clear that the throughput of the odd output ports can be potentially limited due to that unavailability factor. Let δ be the fraction of the N input ports that are available for the second arbitration round, then δN is the expected number of odd queues that are allowed to switch an HOL cell to an odd destination port. In [5] we show that the maximum throughput of the odd outputs is given by $\lambda_O = 1 + 2\delta - \sqrt{[4\delta^2+1]}$ where δ is expressed as $\delta = 1-(\lambda_E/2\rho_E)$. We finally have that the throughput of the odd-even switch is approximated by $\gamma_{max} = [(\lambda_O+\lambda_E)/2] \simeq 0.705$ which is in very good agreement with our simulation results [4].

Extensions: We can extend our odd-even model by allowing m (instead of two) FIFO queues where an incoming cell is buffered according to its output destination [5]. Under our policy A, an input port can release only up to one cell. We further modify our proposed switching architecture where all queues (mN in the general scheme), independently participate in a single arbitration phase (this is our policy B, where obviously an input is then allowed to route more than one cell). In [5] we have analysed this last (generalised) model for which we obtained its maximum throughput $\gamma_{max} = 1 + m - \sqrt{[1+m^2]}$. Note that the authors of [1] have proposed, among others, an architecture (and analysis) which is exactly the same as that we presented and studied in [5], policy B, (for $m = 2$). Indeed, their equations, e.g. eqns. 1, 4 and 5 are identical in context and notation to ours [5], e.g. eqns. 2, 4, 10 and 12.

24 February 1998
Electronics Letters Online No: 19980457

C. Kolias and L. Kleinrock (*Department of Computer Science, University of California at Los Angeles, Los Angeles, CA 90095-1596, USA*)

E-mail: ck@ucla.edu

References

1 SON, J.W., LEE, H.T., OH, Y.Y., LEE, J.Y., and LEE, S.B.: 'Performance of an input-queued ATM switch with even-odd switching planes', *Electron. Lett.*, 1997, **33**, (14), pp. 1192–1193
2 HUI, J.Y., and ARTHURS, E.: 'A broadband packet switch for integrated transport', *IEEE J. Sel. Areas Commun.*, 1987, **SAC-5**, (8), pp. 1264–1273
3 KOLIAS, C., and KLEINROCK, L.: 'The odd-even switch'. IEEE ATM Workshop '95, Washington, DC, October 1995
4 KOLIAS, C., and KLEINROCK, L.: 'The odd-even input-queueing ATM switch: Performance evaluation'. Proc. Int. Conf. Communications (ICC) '96, Dallas, Texas, June 1996, pp. 1674–1679
5 KOLIAS, C., and KLEINROCK, L.: 'Throughput analysis of multiple input-queueing in ATM switches' *in* MASON, L., and CASACA, A. (Eds.): 'Broadband communications' (Chapman & Hall, London, UK, 1996), pp. 382–393

Severe timing-jitter penalty caused by finite pump linewidth in transmission systems using dispersion compensation via mid-span spectral inversion

D. Gavrilovic and D.D. Marcenac

The authors show, for the first time, that pump linewidth can cause severe timing jitter penalties in transmission systems using dispersion compensation via mid-span spectral inversion (MSSI). A theoretical study of MSSI in 40Gbit/s transmission systems is presented, and simple analytic formulas relating the pump linewidth to the transmission penalty are derived.

Introduction: Ultra-high bit rate transmission is an attractive solution to upgrade the installed non-dispersion shifted fibre (NDSF) infrastructure. However, at 40Gbit/s or above, chromatic dispersion drastically limits the transmission distance. Chirped Bragg fibre grating [1], dispersion compensating fibre [2], and mid span spectral inversion (MSSI) have been used to compensate for dispersion at 40Gbit/s. MSSI is a promising technique as it not only compensates for chromatic dispersion but can also partly cancel the distortions due to fibre nonlinearities [3]. Multiwavelength MSSI with a highly nonlinear fibre phase conjugator has been reported with successful dispersion compensation in a 5 × 40Gbit/s transmission over 105km of NDSF [4]. MSSI using a semiconductor optical amplifier (SOA) as a four-wave mixer has enabled single wavelength 40Gbit/s transmission over 406km [5]. Moreover, whereas polarisation sensitivity limited the usefulness of phase conjugation in commercial applications, polarisation-insensitive