Acknowledgment: The authors would like to thank J. Bass, A. Cornfeld, E. Carlson, R. Dean, S. Huynh and J. Proctor for their technical assistance.

1st October 1992

T. Ho, K. Pande, F. Phelleps and J. Singer (*COMSAT Laboratories, Clarksburg, Maryland 20871-9475, USA*)

P. Rice, J. Adair and M. Ghahremani (*Hercules Defense Electronics Systems, Inc., Clearwater, Florida 33518, USA*)

References

1 KIM, B., MACKSEY, H., TSERNG, H., SHIN, H., and CAMILLERI, N.: 'Millimeter-wave monolithic GaAs power FET amplifiers'. GaAs IC Symp. Dig., 1986, pp. 61–63

2 CAMILLERI, N., CHYE, P., and PRIORIELLO, R.: 'Monolithic 50GHz GaAs FET power amplifier'. GaAs IC Symp. Dig. 1989, pp. 267–270

3 YANG, H., HERMAN, R. M., ANGEL, K. W., and CHAO, A. M.: 'A 0·25-Watt three-stage Q-band MESFET monolithic power amplifier'. GaAs IC Symp. Dig., pp. 161–164

4 HO, T., PHELLEPS, F., HEGAZI, G., PANDE, K., and HUANG, H.: '35 GHz monolithic GaAs FET power amplifiers'. 1990 IEEE-MilCom. Proc., October 1990, pp. 184–186

5 HEGAZI, G., HUNG, H., PHELLEPS, F., CORNFELD, A., SMITH, T., ALLISON, J., and HUANG, H.: 'V-band monolithic power MESFET amplifiers'. IEEE-MTT-S Symp. Dig. May 1988, pp. 409–412

OPTICAL SLOT SYNCHRONISATION SCHEME

Z. Haas

Indexing terms: Synchronisation, Optical communication, Packet switching

A scheme is presented that allows the synchronisation of packets at the input to an optical, synchronously-operated packet switch. The scheme requires only two delay modules and carries a penalty of 50% of the switch capacity.

Introduction and motivation: In wide-area networks, because of the relatively large uncertainty and considerable changes in the optical signal propagation delay, there is the need to continuously synchronise the packet arrival times at the inputs with the local slots of a synchronously-operated optical packet swtich. An example of such a switch is described in Reference 1. Previously proposed schemes rely on a multiplicity of delay devices, each with a fractional part of the packet transmission time, so that nearly any value of delay may be generated and used to compensate for the difference between the packet arrival time and the beginning of a local slot. Such devices are commonly built out of switching modules (such as 2×2 $LiNbO_3$ directional couplers) and fibre delay lines. The difficulty with these schemes is the relatively large power penalty, because of the multiple coupling loss between the modules and the fibre delay lines; i.e. the optical signal travels several times in and out of the $LiNbO_3$ wafers. Here, we present a synchronisation scheme that requires only two switching modules, thus reducing the power penalty. This comes at the expense of 50% in switch throughput.

Synchronisation scheme: Our scheme, termed packet flipping, is based on time slots that are twice longer than the actual duration of the packet. Thus the penalty of this scheme is that the network capacity is reduced by 50%. (Such a reduction is in line with the philosophy that some fraction of the enormous bandwidth can be 'wasted' to provide simpler control or operation of the all-optical networks.) Refer to Fig. 1 for the explanation of the scheme operation. It is assumed that each switching node in the network has a local clock, $clock_{frame}$, with period of 2τ, where τ is the duration of the packet. We call this 2τ-long slot a frame. The clocks at different switches (nodes) are unsynchronised with each other. Moreover, it is assumed that in each switching node (and network interface) only one packet can be placed in a (locally defined) frame.

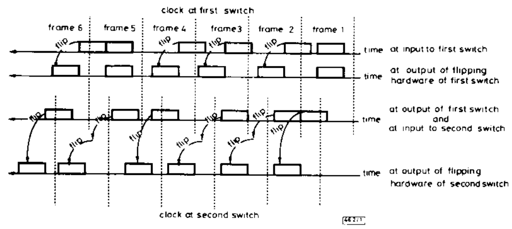

Fig. 1 *Packet flipping scheme for packet synchronisation*

Within this frame, however, the packet may float. If such traffic is presented to an all-optical packet switch with slot size equal to the frame size (i.e. with twice as long slot size), the switch preserves the 'one packet per frame' rule. However, if this traffic coming from the output of the switch is received at the next switching node with unsynchronised local frame clock, the 'one packet per frame' rule may be violated, as shown in Fig. 1. To correct this, so that again there is a single packet per frame aligned with the new local frame clock, the hardware in Fig. 2 is introduced. Each module can either add no extra delay or a delay of τ to the optical signal. If a packet does not fall in between two clock frames or if there are two packets per frame, and extra delay is added to correct this situation. The packet flipping scheme reduces the number of times that an optical signal needs to traverse $LiNbO_3$ wafers, as compared with other optical synchronisation schemes.

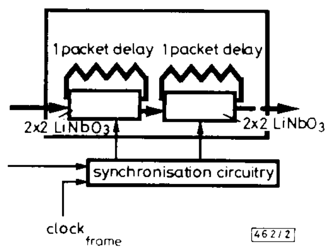

Fig. 2 *Components for packet flipping scheme*

We define the *s characteristic* of traffic with respect to a specific clock, as having the following property:

All the packets in the traffic stream are positioned between the clock ticks. In other words, the traffic might have been generated in such a way that there is only one packet per frame (2τ-long). The packets may, however, 'float' within the frame. In the following, we assume that all clocks are of equal period 2τ and prove that *s-characteristic* traffic with respect to any clock can be made *s-characteristic* with respect to a specific clock by the hardware shown in Fig. 2.

Consider the time diagram in Fig. 3. In this Figure (case 1 and case 2) is shown a transmission of four packets with two (unsynchronised) clocks A and B. The traffic has the *s characteristic* with respect to the frames of clock A (i.e. A_1, A_2, A_3, and A_4), but not with respect to clock B. For clock A, time is measured on axis t, and for clock B, time is measured on axis t'. We will show how to convert the traffic, so that it exhibits the *s characteristic* with respect to the clock B.

We denote the offset of clock B from clock A by δ; i.e. $t_A - t_B = \delta$, where t_A and t_B are the clock instances of clock A and B, respectively. Assume case 1, where $\tau \leq \delta \leq 2\tau$. In this case, we use one of the delay lines of delay τ to offset the transmission, so that we can now assume that $0 \leq \delta \leq \tau$, as in case 2. What remains to be shown is that when $0 \leq \delta \leq \tau$, using a single delay line of delay τ restores the *s characteristics* of the traffic with respect to clock B (case 2).

To prove the above, associate each frame of clock A with a frame of clock B, as shown in the Figure (i.e. A_1 is associated with B_1, etc). Now, the claim is that under the above conditions, a packet either fits in a frame of clock B, or can be delayed by τ and now fits in the frame. If a packet fits in the clock B frame, nothing needs to be done. This happens when $\delta \le t_i \le 2\tau$, where t_i is the arrival time of packet i. On the

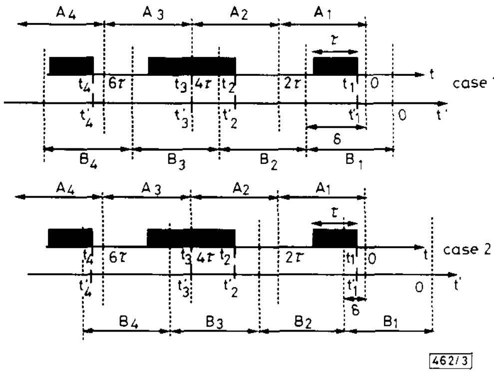

Fig. 3 *Time diagram for proving packet flipping algorithm*

other hand, if a packet 'falls' on the B clock (i.e. when $0 \le t_i \le \delta \le \tau$), the packet needs to be delayed by τ ('flipped'). When this happens, the time of arrival of packet i on the t' axis will be: $t_i' = t_i - \delta + \tau$. However, because $0 \le t_i \le \delta \le \tau$, it follows that $0 \le \tau - \delta \le t_i' \le \tau$. Thus, after flipping, the packet will fit into the clock B frame.

A switch with frames of size 2τ preserves the *s characteristic* of traffic with respect to the local clock, thus if the input traffic to the first switch in a series of switches is *s characteristic* with respect to any clock, by using the flipping hardware in front of every switch, the traffic presented to every one of the switches can be made *s-characteristic* with respect to every local clock.

22nd September 1992

Z. Haas (*AT&T Bell Labs, Room 4F-501, PO Box 3030, Holmdel, NJ 07733, USA*)

References

1 HAAS, Z.: 'Staggering switch': an 'almost-all' optical packet switch', *Electron. Lett.*, 1992, **28**, (17), pp. 1576–1577

SUBPICOSECOND SOLITON PULSE FORMATION FROM SELF-MODE-LOCKED ERBIUM FIBRE LASER USING INTENSITY DEPENDENT POLARISATION ROTATION

D. U. Noske, N. Pandit and J. R. Taylor

Indexing terms: Pulse generation, Soliton transmission lasers, Optical fibres

Pulses as short as 765 fs have been generated from an erbium doped, unidirectional, fibre ring laser, mode locked using the effect of intensity dependent polarisation rotation. The output from the laser exhibits all the characteristics of temporal and spectral instability expected from a periodically amplified soliton system when the amplification length is a significant fraction of the soliton period.

Intensity dependent polarisation rotation has been used for some time as a mechanism to mode-lock bulk laser systems [1]. In optical fibres, the same effect has been used with considerable success as a mechanism for removing low level pedestal components from the output of mode-locked fibre lasers and fibre-grating pulse compressors [2, 3]. Pedestal suppression using this technique has also been observed in the 'soliton' regime, using a relatively long length of low birefringence fibre operating in the multibeatlength regime [4]. Recently there has been renewed interest in multibeatlength all-optical fibre switching in standard low birefringence fibres [5]. The process of intensity dependent polarisation rotation can also be readily used as an ultrafast saturable absorber for the selfstarting, passive mode locking of fibre lasers and this has been described by Mollenauer* for picosecond soliton generation in an erbium based system. Operation of the laser described by Mollenauer has been theoretically modelled by Chen *et al.* [6]. Self-starting, picosecond soliton operation has also recently been reported by Matsas *et al.* [7] for a passively mode locked erbium fibre ring laser. Here we report subpicosecond soliton generation from an optimised erbium fibre ring laser, mode locked using the intensity dependent polarisation rotation mechanism.

A schematic diagram of the laser system is shown in Fig. 1. The pump radiation was provided by a CW argon ion laser pumped titanium sapphire laser providing up to 350 mW

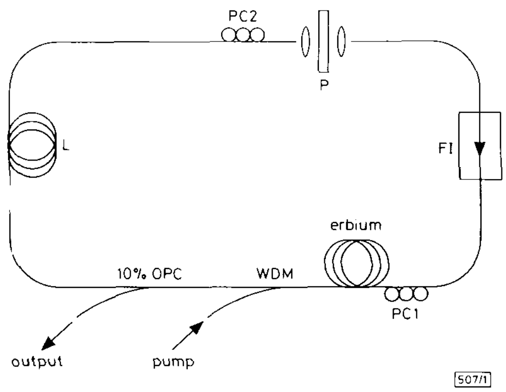

Fig. 1 *Schematic diagram of experimental arrangement*

average power at 980 nm in the fibre. This was coupled into the fibre laser via a standard 980 nm/1550 nm WDM to excite an 8 m length of erbium doped fibre ($\sim 1000\,ppm$ Er^{3+} in an SiO_2-Al_2O_3-P_2O_5 host). Undirectional operation of the fibre laser was controlled by the inclusion of a polarisation independent Faraday isolator (FI). The intensity dependent state of polarisation was controlled through a length L of standard, singlemode telecommunications fibre placed between two polarisation controllers/strainers (PC1, PC2), followed by a polarcor, dichroic glass polariser P, placed in a fibre pigtailed beam expander. Initially a 245 m length of the standard fibre L was used, which was many times its beat length of a few metres. This step-index fibre, singlemode at $1{\cdot}55\,\mu m$, with a cutoff at $1{\cdot}2\,\mu m$, had a minimum dispersion at approximately $1{\cdot}31\,\mu m$ and a group delay dispersion of 16·5 ps/nm/km at $1{\cdot}55\,\mu m$. The output from the laser was taken via a 10% fibre coupler. The overall loop length of this initial fibre laser was 270 m.

Self-starting, self-mode-locking was achieved with this laser system, simply by increasing the pump power and adjusting the relative orientation of the polarisation controllers while observing the laser output on a scanning spectrograph and background free autocorrelator. Once mode-locked operation had been achieved, the average pump power could be reduced to below 50 mW while still maintaining mode-locked and soliton operation. Fig. 2 shows the typical spectrum obtained for the fibre laser with an overall loop length of 148 m. The insert shown in Fig. 2 shows the associated background free autocorrelation trace, indicating a soliton pulse width of 1·5 ps. Curve fitting to the autocorrelation trace showed it to be an excellent fit to a $sech^2$ pulse shape. Distinct spectral

* MOLLENAUER, L. F.: 1991 Operation of this picosecond laser system, similar to that described in [7] was reported during several lectures in the UK