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Demonstration of 40 Gbit/s optical packet synchronisation using fibre Bragg gratings and fast-tunable wavelength converters

C.-H. Chen, D. Wolfson, L.A. Johansson, D.J. Blumenthal and L.A. Coldren

A method of all-optical synchronisation is proposed and demonstrated at 40 Gbit/s. Based on pre-programmable fibre Bragg grating array and fast-switched widely-tunable wavelength converters, negligible power penalty is achieved up to 1 μs delay as well as 100% layer 2 throughput.

Introduction: All-optical packet switching networks [1] are becoming the solution of fast-growing telecommunication with the advantages of scalability and efficiency by reducing O/E/O conversion and higher available data rate beyond current electronic routing technologies. To ease the design of the key component, the optical packet switch, the incoming packets need to be aligned to a common time reference to eliminate the delay variations introduced by factors such as different routes in networks, fibre chromatic dispersion and thermal expansion in the links. The start of the arriving packet can be determined by a packet delineation function beforehand. Once the packet delineation has been carried out, the synchroniser can be configured by an electronic signal corresponding to the time difference between the arriving packet and the reference clock. In this Letter, a method of optical packet synchronisation based on fibre Bragg gratings (FBGs) combined with tunable wavelength converters (TWCs) [2–4] is proposed and demonstrated.

The configuration is shown in Fig. 1. A series of FBGs with different centre wavelengths are deployed along the fibre to form a wavelength-dependent delay line. The header part of the incoming packet is removed before the optical synchroniser. During synchronisation the payload is converted by a rapidly-tunable WC to one of the FBG centre wavelengths according to the required delay value. The outgoing delayed payload is then forwarded to the next switching stage where it is converted to a desired wavelength by the second TWC. Here we use an InP-based Mach-Zehnder interferometric wavelength converter monolithically integrated with a fast tunable SGDBR as characterised in [4, 5]. It has an output switching window of 6 ps, extinction ratio >9 dB, less than 4 dB power penalty at 10^{-9} BER and low pattern dependence across a 25 nm tuning range operating at 40 Gbit/s using RZ signals, which demonstrate its feasibility for this application.

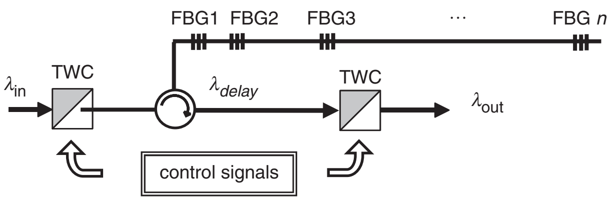

Fig. 1 *Schematic structure of optical packet synchroniser*

The proposed method benefits from low insertion loss and a long available maximum delay up to several microseconds because of the nature of optical fibre. It furthermore decreases the required number of spools for different delay values to potentially one. Also with the fast-switching widely-tunable wavelength converter, rapidly selectable [6] discrete delay values and a large number of channels are attainable. For the 200 GHz channel spacing used in this work, more than 20 channels in the C-band and more than 60 channels in C + L-band are achievable depending on the tuning range of the wavelength converter. Moreover by using interleavers, or 100 GHz channel spacing, the number of channels can be doubled. Note that it is not necessary that the channels are on the ITU grid since they are internal channels.

Experiments: For initial demonstration of functional feasibility at 40 Gbit/s, a configuration of four FBGs with 100 GHz reflection bandwidth and 200 GHz channel spacing serially connected to a three-port circulator was established. The fibre lengths between adjacent FBGs were designed with an exponential increment. Dispersion compensation fibre (DCF) of 345 m is added before FBG4 to compensate the non-negligible fibre dispersion. The delay of each FBG channel and its centre wavelength is listed in Table 1. Preliminary characterisation has also been reported in [7].

Table 1: Experiment results

	FBG1	FBG2	FBG3	FBG4
Centre λ	1553.55 nm	1550.22 nm	1551.91 nm	1558.88 nm
Time delay results				
Time delay to FBG1	0	0.029 μs	1.06 μs	10.47 μs
Fibre length to FBG1	0	2.9 m	106 m	1047 m
Short pulse input measurement				
Input T_{FWHM}	6.55 ps	6.02 ps	6.56 ps	8.07 ps
Output T_{FWHM}	10.25 ps	9.90 ps	10.17 ps	10.82 ps
Pulse spreading	3.7 ps	3.88 ps	3.61 ps	2.75 ps

The insertion loss can ultimately be reduced to the fibre transmission loss (< 0.2 dB/km) and the FBG reflectivity; with current bandwidth and channel spacing the crosstalk is below −25 dB which gives negligible passband loss. It enables realisation of large numbers of different delay values and thus resolution. The raised-cosine FBG weighting function provides a Gaussian-like reflected pulse with no apparent sidelobes in the time domain. The pulse spreading is measured to be less than 4 ps for the four channels. It is shown that the broadening effect in the first three FBGs is dominated by the filtering effect while in the case of FBG4 with long fibre it is dominated by the fibre dispersion due to non-perfect compensation. For a 6 ps pulse generated by the TWC [4], the delayed pulse was demonstrated to remain well within the 40 Gbit/s bit slot.

Bit error rate and layer 2 results: The bit error rate for the PRBS 40 Gbit/s RZ operation is measured with an SHF 50 Gbit/s BERT. Four sets of curves corresponding to four FBG channels and their back-to-back signals are shown in Fig. 2. Negligible power penalty is measured for the first three channels with a fibre distance up to 100 m (round trip 200 m). No obvious signal degradation is observed for FBG1, 2 and 3. However for FBG4 with longer fibre length a power penalty of less than 2 dB is measured. It is believed that this penalty can be eliminated if more careful dispersion management is used.

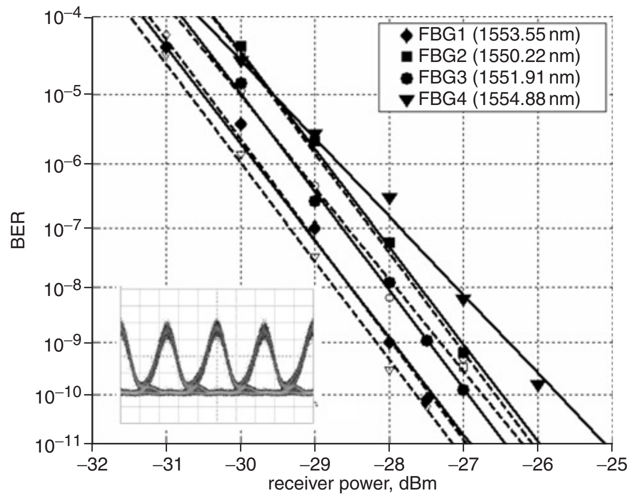

Fig. 2 *Bit error rate measurement for four FBGs*

Back-to-back signals (dashed lines) and FBG signals (solid lines) shown
Inset: Eye diagram for back-to-back signal at 1553.55 nm

To further understand the packet level recovery behaviour, a layer 2 measurement, which was defined in [8], is presented. The layer 2 measurement here is defined as capturing the payload stream and calculating how many payloads are captured. The received optical payload stream was stored in the BERT internal RAM, and then transferred to a personal computer for analysing by software. By calculating how many payloads are correctly captured, the payload recovery curves can be generated. The payload stream with 8 ns payload length and 100 ns guard band is uniquely identified by a 64-bit field as used in [8]. As shown in Fig. 3, 100% payload recovery is possible for all four channels with proper optical power. It is noticeable that about 3 dB negative penalty at 90% recovery rate was measured. One possible cause of negative penalty is the spectral filtering effect for the reflection band of the FBGs. By looking at the BER curves in Fig. 2, owing to the slope difference between the back-to-back and FBG signal, it has a crossover at high bit error rate values for each channel as can be seen by extrapolating the curves. Also, according to previous experience it is inferred that the noise statistic has been changed for high error-rate range, thus different error-rate behaviour.

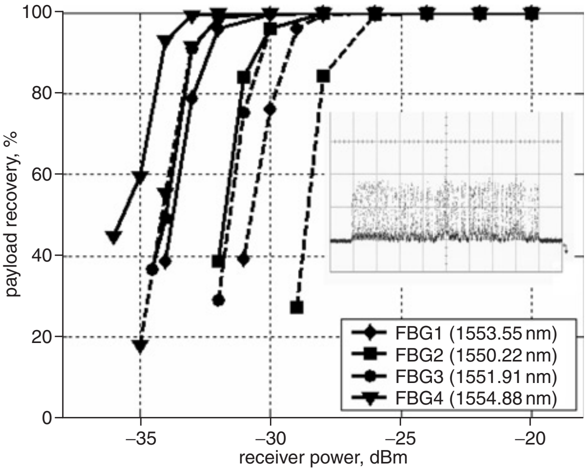

Fig. 3 *Layer 2 payload recovery measurements*

Recovery curves of back-to-back (dashed lines) and four FBG channels (solid lines) shown
Inset: Packet stream used in layer 2 measurements

Conclusion: An optical packet synchroniser with a large number of rapidly selectable discrete delay values, low insertion loss and long available maximum delay is established by the proposed method of using FBG array and fast-tunable wavelength converters. 40 Gbit/s RZ negligible power penalty up to 1 μs and <2 dB power penalty for more than 10 μs was obtained. Also, layer 2 packet recovery measurements show that 100% payload recovery is possible.

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