systems. The correspondingly large amount of pulse breathing which can rapidly lead to unacceptable signal degradation through pulse interactions. In our experiment there was a rapid increase of the ~7ps pulse width away from the transform limited point in the dispersion map to as much as 100ps at the junction of the DCF and the SF. For error-free detection, it is crucial that the data stream is extracted at a point close to the transform limited position in the dispersion map and, thus, that it is injected at an appropriate position within the dispersion map. In our experiments, the injection point is close to the mid-point of the SF span, as depicted in Fig. 1. To simulate potential upgrade, the DCF was located adjacent to the EDFA, with lengths of SF before and after this combination. It is interesting to note that although dispersion managed soliton transmission techniques have been utilised here, as in the numerical simulations reported in [6], the quasi-linear RZ experimental pulses did not exhibit the usual energy enhancement associated with dispersion managed solitons. Indeed, the low value, ~11fJ, of the optimum pulse energy was comparable to that of a fundamental soliton in the equivalent uniform dispersion system.

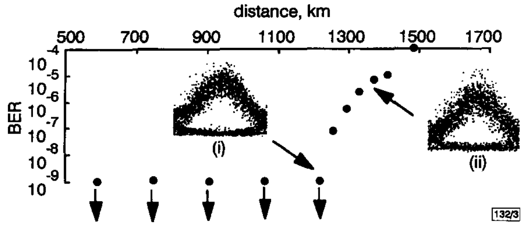

**Fig. 3** *BER against propagation distance results for 10Gbit/s demultiplexed channel showing demultiplexed eye*

(i) after 1220km
(ii) after 1411km

The measured average BER against propagation distance for all channels is given in Fig. 3. These results demonstrate that a BER of $< 10^{-9}$ was maintained after 32 recirculations of the loop, corresponding to a total transmission distance of 1220km (1009km of standard fibre) or 1254 dispersion lengths. The insets in Fig. 3 give the measured eye diagrams corresponding to (i) 1220km and (ii) 1411km transmission distances, and indicate that the eye closure after propagation was due to timing jitter. The most likely cause of this jitter is pulse interactions although Gordon-Haus effects may also contribute in small part. There was no significant eye closure ascribable to an increase in the noise level. Although the demonstrated propagation distance is the greatest yet achieved over standard fibre at 40Gbit/s, it falls short of the ~2000km limit predicted by numerical simulations [6]. One likely contributable reason is that lack of ideal fibre lengths for our experiments precluded positioning of the amplifier within the DCF span, corresponding to the optimum position determined numerically. Further investigation of this, along with further optimisation of the data insertion/extraction point in the SF span, should close the gap.

*Conclusions:* We have performed a single polarisation, single channel 40Gbit/s transmission experiment over standard fibre with an error-free (BER $< 10^{-9}$) propagation distance of 1009km of standard fibre. This distance is a new record over standard fibre and furthermore it was achieved using the entirely passive technique of dispersion management. This result shows that existing short-haul standard fibre links can easily be upgraded to 40Gbit/s. Although the amplifier span in our experiment (39km) was restricted by the DCF available, the fact that the system was not noise limited is an indication that a larger amplifier spacing may be possible.

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# 320-channel multiplexer consisting of 100GHz-spaced parent AWG and 10GHz-spaced subsidiary AWGs

K. Takada, H. Yamada and K. Okamoto

A 320-channel multiplexer with a channel spacing of 10GHz in the 1.55μm wavelength region is reported. This was achieved by using subsidiary 10GHz-spaced AWGs connected in parallel to a parent 100GHz-spaced AWG. A pair of input/output ports in every subsidiary AWG were optically connected to the parent AWG. The crosstalk to neighbouring and all other channels was < –20dB.

*Introduction:* Large-scale multiplexers with a narrow channel spacing are very attractive for increasing the capacity of waveguide division multiplexing (WDM) systems, and arrayed-waveguide gratings (AWGs) [1] are very promising components for WDM applications. Although several attempts have been made to increase the AWG channel number, the largest number achieved so far is ~128 [2] and this is limited by the dimensions of the available substrates and the phase error produced in both the phased array and the slab waveguides of the AWGs.

We report a larger-scale multiplexer that uses a parent AWG and subsidiary AWGs, where a pair of input/output ports in every subsidiary AWG were optically connected to the parent AWG. This was achieved by utilising an $N \times N$ multiplicity of subsidiary AWGS and imposing bandwidth and periodic conditions on these AWGs. This configuration allows us to construct a multiplexer with a large number of channels by using conventional AWGs with low channel crosstalk. We set up a 320-channel multiplexer with a channel spacing of 10 GHz and a channel crosstalk of < –20dB by using 100 and 10 GHz-spaced AWGs.

*WDM configuration:* The configuration of the multiplexer is shown in Fig. 1. It consists of one parent AWG with a channel spacing of 100GHz and 16 subsidiary AWGs, AWG $k$ ($k$ = 1, 2, ..., 16), with a channel spacing of 10GHz. The channel numbers, channel spacings, free spectral ranges, and passband widths of the parent and subsidiary AWGs are denoted as ($N_p$, $\Delta\nu_p$, $FSR_p$, $BW_p$), ($N_s$, $\Delta\nu_s$, $FSR_s$, $BW_s$), respectively. Then $N_p = 32$, $N_s = 16$, $\Delta\nu_p$ = 100GHz, $\Delta\nu_s$ = 10GHz, $FSR_p$ = 3.2THz, $FSR_s$ = 160GHz, $BW_p$ = 80GHz and $BW_s$ = 4GHz. The parent AWG had flat-top passbands with a channel crosstalk of < –30dB and one input port was used as the multiplexer input port. The subsidiary AWGs had

Gaussian passbands with a channel crosstalk of < −32dB [3]. The input/output ports of the parent and subsidiary AWGs were numbered 1, 2, ... from top to bottom so that the centre wavelength of the passband increased with increasing number. Every output port of the parent AWG was connected to either the input or output port of a subsidiary AWG as follows: The output ports of $j$ and ($j + 8$) were connected to a given pair of input/output ports of subsidiary AWG $j$ through optical fibres, where $j = 1, 2, ..., 8$. The output ports of ($j + 8$) and ($j + 16$) were connected to a given pair of input/output ports of AWG $j$ through optical fibres, where $j = 9, 10, ..., 16$. The rule by which each pair is selected will be described in the following Section. The remaining ports were used as multiplexer output ports. Although optical fibres were used to connect the AWGs in this experiment, planar lightwave circuit technology will enable us to integrate all these AWGs onto one Si chip.

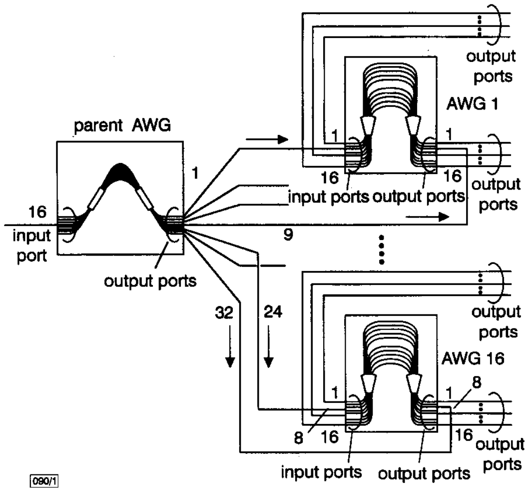

**Fig. 1** *Schematic diagram of 320-channel multiplexer*

Parent and subsidiary AWGs (AWG 1–16) had channel spacings of 100 and 10GHz, respectively

Since the diffraction orders of the subsidiary AWGs were very large, of the order of 1200 at 1.5μm, all the passbands obtained from the $N_s$ (= 16) ports on the opposite side of an incident port at different diffraction orders were arranged at 10GHz intervals without missing any passbands. Changing the incident port shifts these passbands by an integer multiple of 10GHz. The parameters of the AWGs we used satisfied the bandwidth condition of $BW_p < FSR_s$ and the periodic condition of $N_s\Delta\nu_s = FSR_s$. Then all the passbands generated by slicing the passbands of the parent AWG with the subsidiary AWGs were arranged at 10GHz intervals without missing any passbands and they were obtained from the ports of the subsidiary AWGs. Since adjacent passbands of the parent AWG overlapped with a finite value, we selected the better of the two generated passbands with the same centre in the overlap region.

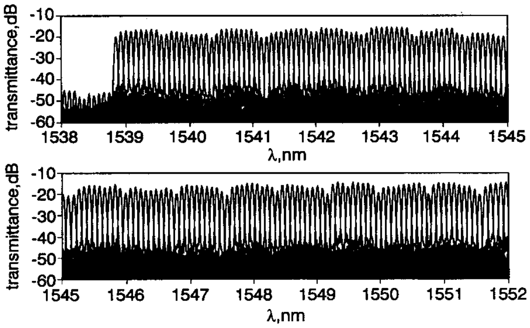

**Fig. 3** *Demultiplexing properties of channels for 1538–1552nm range*

*Experimental results:* Output port 24 of the parent AWG was connected to input port 8 of subsidiary AWG 16 and the resultant passbands generated from 16 output ports are shown in Fig. 2*a*. The bandwidth condition ensured that other passbands with different diffraction orders were well attenuated compared with the main 16 passbands. Of the 16 passbands, 7–9 were attenuated by > 20dB compared with 12–16 and 1–4 because they were at the edge of passband 24 of the parent AWG. The reciprocity theorem states that passbands that are generated from 16 input ports should be arranged in the way shown in Fig. 2*a* when output port 24 of the parent AWG is connected to output port 8 of AWG 16 and so passband 8 from input port 8 should also be sufficiently attenuated.

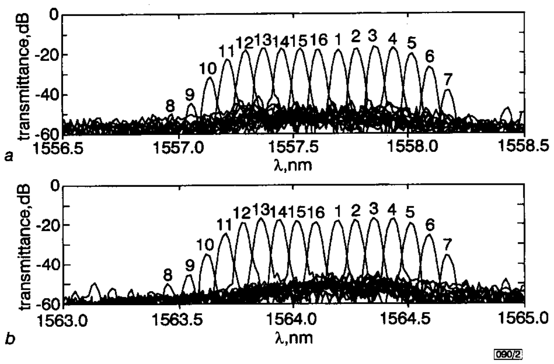

**Fig. 2** *Series of passbands and that were arranged at 10GHz intervals when output ports 24 and 36 of parent AWG were connected to input and output ports of 8 in subsidiary AWG 16, respectively*

*a* Passband for output port 24
*b* Passband for output port 36

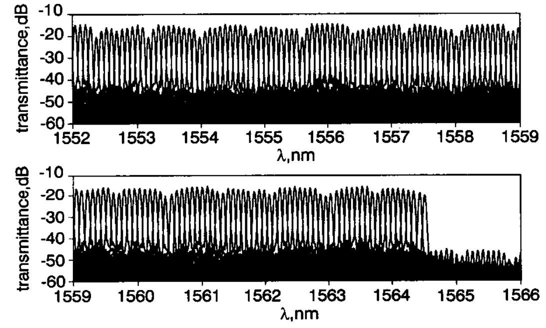

**Fig. 4** *Demultiplexing properties of channels for 1552–1566nm range*

Since the least common multiple of $\Delta\nu_p$ of the parent AWG and $FSR_s$ of subsidiary AWGs is 800GHz, the same pattern as that shown in Fig. 2*a* should appear when output port 32 of the parent AWG, the passband centre of which is shifted 800GHz from that of output port 24, is connected to output port 8 of the same AWG 16. The result is shown in Fig. 2*b*. As expected, the order of the 16 passbands was the same as that in Fig. 2*a* and passbands 7–9 were sufficiently attenuated by the same amount. That is, we do not have to obtain the two passbands generated from the input and output ports of 8 and better passbands with the same centres can be obtained from other subsidiary AWGs. Then the two ports can be used solely for connection between AWG 16 and the parent AWG. In this way, we can find such a pair of input/output ports used for the connection as long as two output ports of the parent AWG have passbands with centres shifted by 800GHz.

Figs. 3 and 4 show the demultiplexing properties for the entire 320channels. The passbands were arranged at equal intervals of 10GHz and there were no missing passbands in the 1539–1565nm wavelength range. The crosstalk to the neighbouring channels was < −20dB. The low crosstalk was due to the fact that the parent and subsidiary AWGs both had low crosstalk values of less than −30dB. The total loss ranged from 14 to 21dB mainly because one pair of passbands from the parent AWG overlapped at a value

5dB lower than the peak. This variation can be reduced by using a parent AWG in which the passbands overlap at a higher value. Although 16 subsidiary AWGs were required in this experiment, this number can be halved by doubling their channel number.

*Conclusion:* We have demonstrated a 320-channel multiplexer with a 10GHz (= 0.08nm) channel spacing in the 1.55µm wavelength region. This was achieved by using subsidiary 10GHz-spaced AWGs connected in parallel to a parent 100GHz-spaced AWG, where a pair of input/output ports of every subsidiary AWG were optically connected to the parent AWG. The crosstalk to neighbouring and all other channels was < –20dB and the loss ranged from 14 to 21dB. This configuration allows us to construct a multiplexer with any large number of channels by using conventional AWGs with a low channel crosstalk. Planar lightwave circuit technology will enable us to integrate all the AWGs we used onto one Si chip.

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# 3Tbit/s (160Gbit/s × 19 channel) optical TDM and WDM transmission experiment

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A 3Tbit/s (160Gbit/s × 19 channels) optical signal has been successfully transmitted over 40km of dispersion-shifted fibre. Low noise supercontinuum signal pulse sources and 70nm bandwidth tellurite-based optical amplifiers are used for 3Tbit/s signal generation and amplification.

*Introduction:* Ultra-high bit rate optical transmission technology that offers a transmission rate greater than terabits per second (Tbit/s) will be needed due to the rapid growth in Internet traffic. Following initial Tbit/s transmission experiments [1 – 3], many approaches have been reported to increase the bit rate and, to date, 2.6Tbit/s has been achieved [4]. To further increase the bit rate, broadband wavelength-division multiplexing (WDM) signal generation and broadband amplification techniques are necessary. We have reported 1.4Tbit/s transmission by combining optical time-division multiplexing (OTDM) and WDM based on a supercontinuum (SC) broadband WDM source [5]. Here we report 3Tbit/s (160Gbit/s × 19 channels) transmission through 40km of dispersion shifted fibre (DSF) using SC WDM sources that have flattened and broadened spectra and a gain flattened tellurite-based erbium-doped fibre amplifier (EDFA) [6].

*Experiments:* Fig. 1 shows the experimental setup. The 3Tbit/s OTDM/WDM signal was formed as 19 WDM channels of 160Gbit/s OTDM signals. The wavelength of the 19 channels ranged from 1540 to 1609nm with a channel spacing of 480GHz. The 3Tbit/s signal generator consisted of two OTDM/WDM signal generators; one for the short wavelength region (1540–1566nm) and one for the long wavelength region (1570–1609nm). Each OTDM/WDM generator was composed of a 3Ps, 10GHz modelocked erbium-doped fibre laser, optical modulator, optical amplifier, and SC fibre. To stabilise the SC output spectrum, all components of the generator were polarisation maintaining. The dispersion of the SC fibre decreases from the anomalous to normal region from the input to output and the group velocity dispersion (GVD) of the SC fibre is a convex function of wavelength and has two zero dispersion wavelengths when the peak GVD is in the anomalous region [7], which enabled the generation of a flattened and broadened SC spectrum. The generated 10 Gbit/s SC signal pulses were then time-division multiplexed 16 times and spectrally sliced by arrayed-waveguide grating (AWG) filters [3] and re-combined to generate the 3Tbit/s WDM signal.

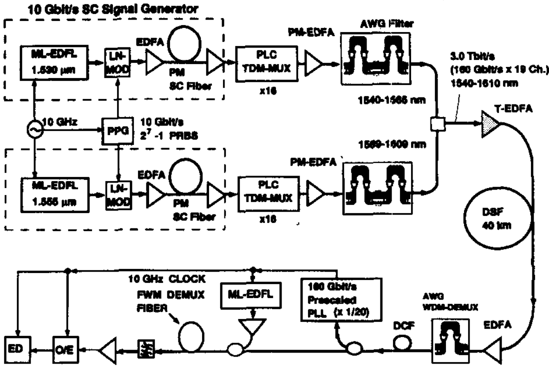

**Fig. 1** *Experimental setup of 3 Tbit/s transmission experiment*

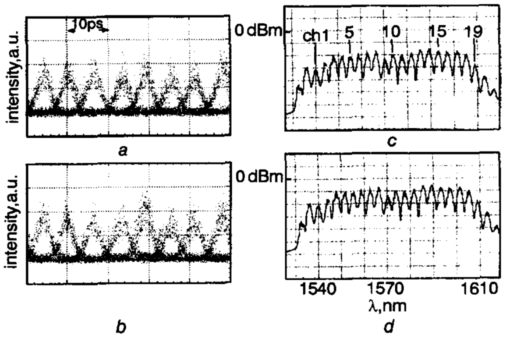

**Fig. 2** *Eye diagram and spectra for 160Gbit/s optical signal*

*a* Eye diagram of 160Gbit/s optical signal at 1552nm before transmission
*b* Eye diagram of 160Gbit/s optical signal at 1552nm after 40km transmission
*c* Spectra of signal at input of tellurite-based EDFA
*d* Spectra of signal at output of tellurite-based EDFA

Fig. 2*a* and *b* show the eye diagram of the 160Gbit/s optical signal at 1552nm before and after 40km transmission, respectively. It is clear from the Figure that good eye opening was observed. The 3Tbit/s WDM signal was then amplified by a 70nm bandwidth tellurite-based EDFA. To obtain the flat gain characteristics, we used two-stage tellurite-based EDFAs and an intermediate gain equaliser [8]. Fig. 2*c* and *d* show the spectra of the signal at the input and output of the tellurite-based EDFA, respectively. A flat gain of 13dB was achieved for all 19 channels. The total optical power launched into the transmission DSF was 20.2dBm. The zero dispersion wavelength of the 40km transmission fibre was 1530nm, so all WDM channels were in the anomalous dispersion region. Almost no degradation in the optical spectrum caused by four-wave mixing was observed after 40km transmission. At the receiver, each channel was split by an optical filter, optically preamplified, and then demultiplexed into a 10Gbit/s signal by an all-optical time domain demultiplexer based on four-wave mixing driven by a 10GHz clock extracted from the 160Gbit/s signal channel [3] and the bit error rate was measured.

Fig. 3 shows the measured sensitivity thresholds ( < $10^{-10}$ bit error rate) for the baseline (filled circles) and the transmitted