gratings. The light reflected from the grating sensors are returned via the switch and the coupler to a scanning Fabry-Perot optical filter and to a detector. The Fabry-Perot (FP) used has a free spectral range (FSR) of 45nm, and thus allows the 12 individual sensor gratings spaced ≥3nm to be used. As previously described [6] we use a simple wavelength detection scheme, whereby the detected signal is differentiated and the zero-crossings of this signal are detected by a PC (laptop), which then records the digital value (16 bits) of the ramp voltage applied to the Fabry-Perot filter. The choice of 16 bit resolution for the FP ramp, and a FSR of 45nm produces a minimum resolvable (least significant bit) wavelength shift of 0.7pm, or an equivalent strain resolution of 0.9µstrain. The FSR of the FP filter, and the voltage-to-wavelength tuning response of the device allow this digital value to be converted to a wavelength shift, and thus a strain reading. The FP ramp is produced at a rate of 287Hz, which allows the strain readings to be averaged over many scans (e.g 2 to >100) to provide better resolution if required without significantly impacting the sampling rate. Measured strains are spooled to disk to allow longterm data retrieval. This processing occurs for each of the 60 elements in the array within a 2.5s interval (with 50 average/sensor), which is a more than adequate sampling rate for most civil engineering applications.

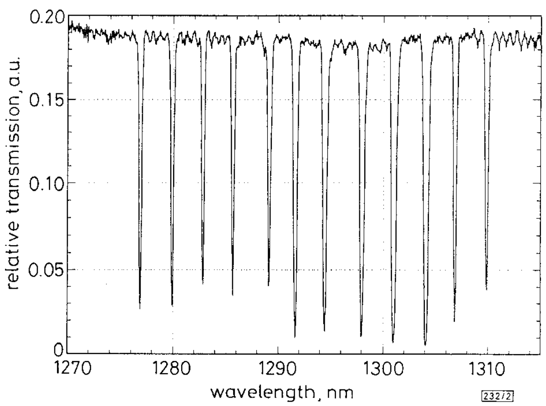

Fig. 2 *Transmission spectrum of one of the five 12 element arrays*

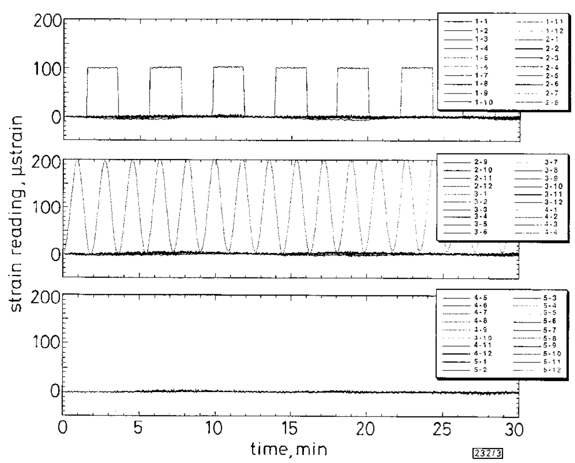

Fig. 3 *Output traces corresponding to all 60 channels over 30min with test strains applied to two grating sensors, 6 (1–6) and 38 (3–2)*

Results: Fig. 2 shows a typical spectrum of the 12 element grating arrays used. A phase-conjugated KrF excimer laser and an uncompensated interferometer were used to fabricate the gratings in H_2 loaded, high delta fibre. The Bragg grating arrays are connected to the electro-optics system via ST optical connectors Fig. 3 demonstrates the performance of the system. Here, the strain responses of the full 60 grating elements were monitored over a 30min period, with test strain perturbations applied to two of the sensor gratings chosen at random: a 0–100 µstrain square wave with ≃ 4 min period applied to grating 6 (1–6), and a 0–200µstrain sine wave with ≃ 2min period applied to grating 38 (3–2). As seen, the longterm performance of the system is excellent, with drifts of only a few microstrain during the recording period. We believe that most of the observed drift, which is seen to be correlated between channels, was due to slight temperature fluctuations in the laboratory. The short-term noise (sample–sample) on the array is ±1µstrain.

Summary: We have described an electro-optics instrumentation system to address 60 FBG sensors, which has the expandability to accommodate several hundred devices. The system represents a second phase prototype instrumentation unit for FBG sensors complete with PC-controlled data acquisition and retrieval.

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Super-step-chirped fibre Bragg gratings

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Indexing term: Gratings in fibres

Concatenation of apodised gratings to form a super-step-chirped fibre Bragg grating structure is demonstrated for the first time. Using this scheme, gratings of arbitrary lengths may be constructed for a predetermined wavelength span.

Introduction: One of the upgrade options for land based transmission systems is the implementation of channelised (1.6nm) wavelength division multiplexing (WDM) and dispersion compensation over route lengths of ~100km at a transmission rate of 10Gbit/s. This option requires a quasi-continuous dispersion compensator with a fixed dispersion. As a result, interest in fibre Bragg gratings (which are essentially narrowband devices) for dispersion compensation has increased dramatically. The method was first proposed by Ouellette [1], but has increased in importance with the fabrication of long chirped fibre Bragg gratings using the scanning method [2]. As the bandwidth of chirped fibre Bragg gratings is reduced, it is necessary to apodise the reflection spectrum so that the delay characteristics remain linear [3]. There are several methods of apodising fibre Bragg gratings [3, 4] and recently we have implemented a simple scheme, using the symmetric stretch of a fibre, which allows the rapid and reproducible apodisation of any type of fibre Bragg grating [5]. It is difficult to fabricate chirped gratings longer than 100mm, however, as will be shown in this Letter, this method allows the apodisation of sequential step-chirped gratings so that specialist wavelength division multiplexed dispersion compensators can be implemented easily. Four 100mm long, sequential wavelength, apodised gratings capable of compensating for dispersion of 1600ps/nm over a bandwidth of 4nm are demonstrated. This super-step-chirped grating (SSCG) has an overall delay of more than 4ns. Further, two concatenated 100mm long unapodised step-chirped fibre Bragg gratings are also shown, in which the stitch between the gratings does not affect the delay characteristics. These demonstrations show the potential of chirped fibre Bragg gratings for dispersion compensation.

Experimental details: The fibre gratings were fabricated using several 100mm long step-chirped phasemasks [6], each designed with sequential start wavelengths [5]. The phasemasks had a bandwidth of ~0.8mm, so that the wavelength separation of every other mask would be separated by the nominal WDM system's specification of 1.6nm. The method used for writing the gratings is based on scanning [2]. The gratings were written into cold hydrogen soaked [7] standard telecommunications, and boron-germanium co-doped fibres [8]. A frequency doubled argon ion laser operating at 244nm was used for writing the gratings. The writing power was ~100mW, and the fibres were scanned between one and 25 times at a scanning speed of 2mm/s. The first set of unapodised gratings was written using the long wavelength followed by the shorter wavelength mask. The end of the first grating was carefully marked on the fibre, so that after translation the second grating could be written sequentially. Thus, the start wavelength of the first grating was λ^1_{long}, while the end wavelength was λ^1_{short}, followed by the second grating start wavelength λ^2_{long} and ending with λ^2_{short}. In principle, several gratings can be written sequentially using this method; apodised gratings for the next set of gratings were carried out using this method. The symmetric stretch apodisation technique [5] was used on each grating in sequential lengths of the same fibre. As before, the end of each step-chirped grating was followed by the beginning of the next. and four gratings were written in a 400mm long piece of the boron-germanium co-doped fibre. Each grating had a 10dB peak reflection (nominal) and was measured for reflection and delay using a vector-Voltmeter and externally modulated tunable laser source [6].

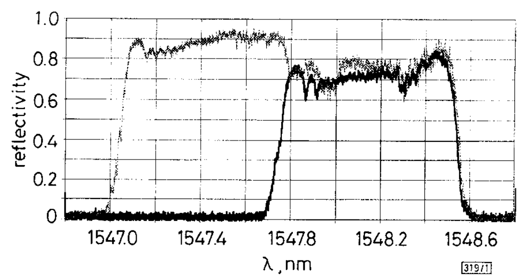

Fig. 1 *Reflection spectrum of a 100mm long unapodised step-chirped fibre grating*

The reflection spectrum of the two UV trimmed concatenated gratings forming the super-step-chirped grating (SSCG) is also shown
SSCG = 200.5mm long
——— reflectivity, G1
·········· reflectivity, G1 + G2

Results: Fig. 1 shows the reflection characteristics of an unapodised step-chirped fibre grating as well as the doubled bandwidth reflection spectrum of two concatenated gratings. Fig. 2 shows the delay characteristics of the first fibre grating, and also after the gratings were concatenated. The stitch between the two gratings was trimmed by post UV exposure [9] over a 0.5mm long, previously unexposed, section between the gratings, by minimising the dip in the reflection spectrum. The delay characteristics are indistinguishable from those of the single grating.

Fig. 3 shows the apodised fibre gratings written with the four phase-masks. Each grating was separated from the last by a few millimetres. In the design of such a device, the dispersion compensation is confined to the bandwidth of each grating. However, the delay characteristics show that WDM dispersion compensators can be fabricated for the wavelength spacing of 1.6nm, currently being discussed for telecommunication systems. The fourth grating was deliberately separated in wavelength from the third by an extra half channel spacing. Notice that the quality of the reflection spectrum has been affected by a drop-out in the phasemask. However. the delay characteristics are remarkably smooth for each grating, and have been used for dispersion compensation over a bandwidth of ~0.5nm each. The bandwidth of each grating varies slightly owing to the non-optimised control on the piezo driver used for apodisation. The overall length of the SSCG is ~400mm, with a total delay of ~8ns. We believe that this grating structure is the longest reported, and constitutes a maior step in the design of WDM components for dispersion compensation. Further sets of four apodised gratings have also been written with a wavelength spacing of ~4nm, spanning a window of 16nm.

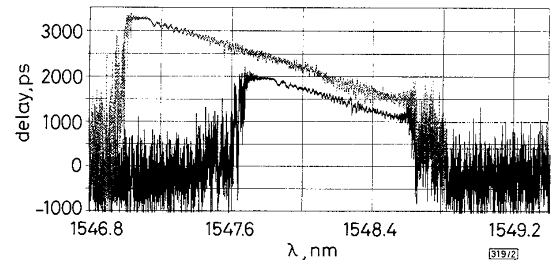

Fig. 2 *Measured delay of the single grating shown in Fig. 1 and that of the SSCG*

——— grating 1 delay, ps
·········· delay, ps, G1 + G2

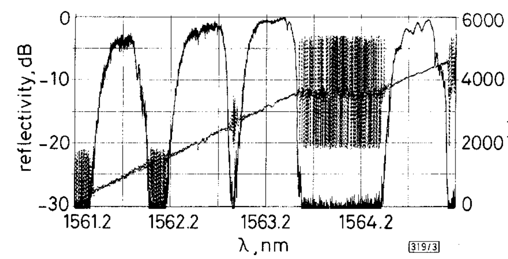

Fig. 3 *Reflection spectrum and delay response of the 400mm long SSCG comprising four 100mm long apodised step-chirped fibre Bragg gratings*

Overall delay of this SSCG is ~4ns, with a discrete dispersion parameter of 1600ps/nm over a 4nm bandwidth. The dynamic range for these measurements was ~30dB
——— reflectivity, dB
·········· delay, ps

Discussion: The first pair of gratings, shown in Figs. 1 and 2, indicates that gratings can be stitched seamlessly. In this demonstration, the mismatch in delay between the two gratings amounts to a step of ~5ps. This step does not pose any problem even for pulses situated at exactly the stitch wavelength. For example, at 10Gbit/s the additional dispersion owing to the step in a typical 100km link is < 4%. Although the delay characteristics of this grating are not ideal for dispersion compensation, the seamless stitching of fibre Bragg gratings has been demonstrated, and is a first step towards the fabrication of long grating structures.

For the second set of four apodised gratings, the stitching between the gratings is of no consequence. For WDM systems separated by specified wavelengths, the dispersion compensating device shown in Fig. 3 adequately demonstrates the principle of concatenation and the SSCG. The repeatable action of the apodising scheme, and the possibility of fabricating phasemasks at a predetermined wavelength separated by ~0.8nm, indicates that dispersion compensation of 100km links can be effectively achieved. This is not a limit of the technique, since a narrower bandwidth, and therefore a higher dispersion step-chirped phasemasks, have also been fabricated at BT Laboratories. Systems measurements have been made at 10Gbit/s using the SSCGs over 120km of optical fibre, and will be reported elsewhere.

Conclusions: Super-step-chirped fibre Bragg gratings have been demonstrated for the first time. A dispersion of 1600ps/nm over a quasi-continuous bandwidth of ~4nm is reported. The principle may be easily extended to span the entire erbium amplifier window. Also demonstrated is the seamless stitching of two unapodised fibre Bragg gratings using UV trimming for the first time.

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Low power all-optical switching in a nonlinear optical loop mirror using chalcogenide glass fibre

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Indexing terms: Photonic switching, Nonlinear optics, Optical fibres

All-optical switching is demonstrated using a nonlinear loop mirror containing a low loss As_2S_3 based fibre module. The gate power is reduced to as little as 0.4W(peak) using a 4m long As_2S_3 fibre. Demultiplexing of a 40GHz pulse train to 4GHz is demonstrated.

All-optical switching will play a crucial role in future high speed optical communication. As_2S_3 based chalcogenide glass fibre has been found to have a large nonlinear refractive index and promising properties as a nonlinear optical medium for all-optical switching [1, 2]. We previously demonstrated a laser-diode-driven optical Kerr shutter that uses an As_2S_3-based glass fibre at a gate power of 3W with the aid of an erbium doped fibre amplifier (EDFA) [2]. In that study the gate pulse repetition rate was limited to 100MHz because the gate pulse average power was limited by the saturation power of the EDFA. Future actual application will require a gate pulse repetition of more than 1GHz; accordingly the gate peak power should be reduced further to achieve higher repetition. In this Letter we demonstrate a lower power (0.4W) all-optical switching using a nonlinear optical loop mirror (NOLM) containing chalcogenide glass fibre [3].

Table 1: All-optical switching performance using As_2S_3 based fibres

Configuration	Fibre fabrication method	Core size	Loss	Fibre length	Switching power	Gate pulse repetition
		μm	dB/m	m	W	GHz
Kerr	Double crucible	6.0	0.9	2.0	11.0	0.1
Kerr	Double crucible	3.0	3.0	1.2	3.0	0.1
NOLM (this study)	Rod in tube	2.5	0.6	4.0	0.4	4.0

Table 1 summarises the results of our recent study of all-optical switching using chalcogenide glass fibres [1, 2]. In an earlier study, we used chalcogenide glass fibre made using the double crucible method [4]. The smaller core size afforded by this method is advantageous in reducing the switching power but could lead to larger scattering loss. In this study we used an As_2S_3 based glass fibre made using the rod-in-tube method [5]. Although this fibre has a small core size, the loss was suppressed to a relatively small value, as shown in the table. We have previously used an optical Kerr shutter configuration [1, 2]. The optical Kerr shutter is useful in checking the extent of nonlinearity, but it does not necessarily provide the smallest switching power. It uses the phase shift difference between two signal components whose polarisation is parallel and perpendicular to that of the gate. Parallel and perpendicular polarisations suffer phase shift. In isotropic materials such as glass, the difference in phase shift is two thirds of the phase shift of the parallel polarisation component [6]. By comparison, the NOLM uses the difference in phase shift between two signal beams that propagate in the same and the opposite directions as the gate pulse [3]. If the gate pulse width is much shorter than the pulse period, the phase shift in the counter-propagating beam is negligible. Thus the phase shift difference is nearly equal to the phase shift of the copropagating beam. The NOLM configuration is consequently advantageous in reducing switching power.

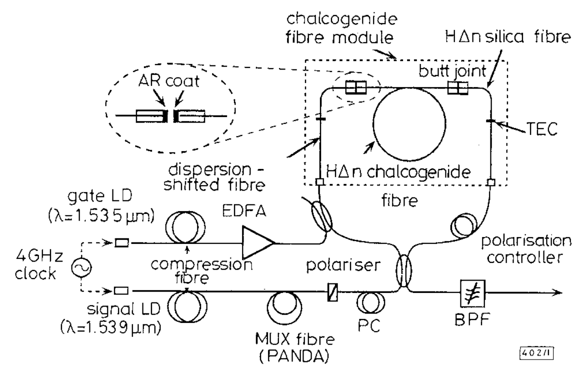

Fig. 1 *Experimental set-up for all-optical switching using NOLM*

Fig. 1 shows the experimental setup. To construct a NOLM with As_2S_3 based fibre, we fabricated a chalcogenide fibre module consisting of a 4m long As_2S_3 based fibre, a small-core silica-based fibre (mode field diameter = 3.9μm), and a conventional dispersion-shifted fibre. Appreciable reflection in the fibre loop in the NOLM might degrade the on-off ratio of switching and lead to bit error in demultiplexing applications. To prevent Fresnel reflection from the interface between the small-core, silica-based fibre and the As_2S_3 based glass fibre with large refractive index ($n \simeq 2.4$), the edges of both fibres were anti-reflection-coated and buttjointed. The small-core silica-based fibre was spliced to the conventional dispersion-shifted fibre using TEC (thermally diffused expanded core) technology [7]. The total insertion loss was 6.3dB and the reflection from the fibre module was measured to be <0.4%. Gate and signal pulses are generated by gain switching of DFB laser diodes and compression with positive dispersion fibre. Relatively close wavelengths were chosen for gate and signal to suppress the walk-off effect [1]. The group delay mismatch between gate and