spans (0.24dB/km loss) and three 1480nm-pumped EDFAs (noise figure = $2n_{sp}/\eta_{in}$ = 7dB). The span dispersion is $D = 0.15$ps/(nm km), corresponding to a mean soliton power of 5 ± 1dBm at the EDFA output. The RF clock, which is locally recovered at 40GHz through a $Q = 300$ filter (limiting the PRBS sequence length to 2^7–1), is split with independent phase adjustments to drive the MZ for either single-electrode or push-pull operation. An optical bandpass filter of 0.7nm optimised width is inserted before the MZ for further jitter/noise control [1]. Bit error rate (BER) measurements are made at 10Gbit/s after demultiplexing through a PI electroabsorption modulator; error-counting is made by randomly sampling the four 10Gbit/s tributaries. The evolution of amplitude Q-factor with distance was measured at two operating points of the regenerator: either (*a*) single-electrode (#2), or (*b*) both electrodes in push-pull mode. In the first case (*a*), the operating point is (V_1, V_2, P_{RF2}) = (0V, –2.5V, +24dBm). The corresponding insertion loss and IM depth are measured to be 16.1 and 7.0dB, respectively. In the second case (*b*), the effective PM depth is adjustable; in the experiment, it was heuristically set to minimise the BER. The operating point was then $(V_1, P_{RF1}, V_2, P_{RF2})$ = (–0.7V, +11dBm, –1.1V, +26dBm), yielding a 16.3dB insertion loss and 7.2dB IM depth.

Fig. 4 shows the Q-factor measurements. In each case, the Q-factors are seen to reach asymptotic values, as predicted by numerical simulation [6]; these measurements represent the first experimental confirmation of such an effect. The slight undershoot is attributed to a correction in the temporal interleaving of the four 10Gbit/s OTDM tributaries. With single-electrode and dual-electrode drive, the asymptotic Q-factors are 6.6 (BER = 10^{-11}) and 7.2 (BER = 10^{-12}), respectively. The improvement in the second case can be attributed to the higher IM depth and optimised PM depth. Strictly identical results were obtained with a 40Gbit/s OTDM signal having random polarisations in the four 10Gbit/s tributaries, showing that the regenerator has truly polarisation-independent behaviour. Very stable operation of the loop was observed in either case, with no BER change over several hours.

Potential crosstalk effects were then investigated. Two uncorrelated WDM signals at λ_1 = 1555.8 nm and λ_2 = 1558.3nm with 40Gbit/s, 2^{15}–1 PRBS coding were synchronously input to the modulator in push-pull mode, driven by the fourfold-multiplied, 10GHz transmitter clock. Fig. 5 shows the BERs against decision threshold for both channels, along with similar measurements when an attenuator with the same loss (16.3dB) replaced the modulator. With/without the MZ, the Q-factors were found to be 7.6/7.7 at λ_1 and 8.3/8.5 at λ_2. The negligible penalty observed for both channels under simultaneous WDM modulation effectively demonstrate an immunity to interchannel interference.

In summary, a new type of 40GHz polarisation-insensitive and wavelength-independent regenerator has been implemented. Its dual-electrode configuration makes it possible to separately control IM and PM, resulting in enhanced BER performance, as demonstrated by a 20Mm, 40Gbit/s error-free ($Q > 7$) transmission experiment. Immunity to WDM crosstalk was also observed, showing the potential of simultaneous WDM regeneration.

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Amplification in 1.2–1.7μm communication window using OPA in PPLN waveguides

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Highly nonlinear (up to ~2000%/W) parametric amplifiers in periodically-poled $LiNbO_3$ waveguides are presented. High optical gain (up to 90dB) in the whole transmission window of silica optical fibres has been obtained using fibre laser pump sources.

The dramatic increase in recent years in the level of communication network traffic necessitates further developments of high capacity communication systems. With the emergence of dense wavelength division multiplexing (WDM) the most important remaining technological bottleneck is the limited spectral range accessible to optical amplification with fibre amplifiers. The maximum bandwidth of state-of-the-art Raman and Er-doped fibre amplification systems at 1.55μm is only 50–80nm. These amplifiers cannot be tuned or wavelength tuning is very difficult, and therefore to cover the full transmission window from 1.2 to 1.7μm for low-loss silica fibre cables, new types of optical amplifiers must be developed.

We demonstrate here that optical parametric amplification (OPA) in proton-exchanged waveguides in periodically poled $LiNbO_3$ (PPLN) can be used for amplifying signals in optical communication systems at any wavelength within the 1.2–1.7μm spectral range using relatively low pump powers from fibre-based sources. We report waveguide structures with effective nonlinearities for parametric interactions of up to 2000%/W, sufficient for achieving > 20dB gain with pump peak powers at ~1W level. In addition, we demonstrate fibre laser pumped optical parametric generation (OPG) in these waveguides, thus providing convenient signal sources tunable over this broad spectral window.

The optical gain G for a given pump power P_{pump} in a guided-wave parametric amplifier is given by

$$G = \frac{1}{4}\exp\left(2\sqrt{\eta P_{pump}}\right) \qquad (1)$$

where η is the effective waveguide nonlinearity. Previously, OPA has been considered impractical for fibre optic communication systems due to the need for unacceptably high pump powers. Indeed, the best OPA (and OPG) reported previously in $LiNbO_3$ quasi-phase-matched waveguides exhibited η in the range 20–40%/W at best [1, 2]. The resulting peak powers of tens of watts required for CW or high-repetition-rate pulsed pumping are sufficiently high to cause significant problems related to optical and photorefractive damage in these devices. Here, we report a significant increase in the effective waveguide nonlinearity, which was achieved by modifying the cross-sectional overlap between the pump and signal modes. This maximised the spatial overlap integral between these interacting modes and reduced the detrimental effect of the 'dead' layer in the proton-exchanged region of a waveguide structure [3]. Additionally, we increased the interaction length by fabricating long waveguides with sufficient homogeneity of the effective refractive index along the beam propagation direction.

Long annealed proton-exchanged channel waveguides were fabricated on three-inch z-cut electrically poled $LiNbO_3$ substrate wafers of 0.5mm thickness. The basic device structure is shown in Fig. 1. It consists of two sections: a 1mm long second-harmonic generator (SHG) at the input and an OPA section with different lengths L from 1 to 5cm at the output. The waveguides were designed for pumping at ~1560nm with Er-doped fibre sources. The use of an SHG section allows two aims to be satisfied. First, pump wavelength up-conversion to ~ 780nm is necessary for pumping OPA and OPG in the 1.2–1.7µm range. Secondly, a particular non-fundamental pump mode (e.g. TM_{01}) can be excited selectively in this section by an appropriate choice of quasi-phase-matching (QPM) period Λ for SHG: $\Lambda = \lambda_\omega/(2(n_{2\omega\text{-mode}} - n_{\omega\text{-mode}}))$. In Fig. 2*a* the calculated depth-distribution profiles for TM_{00} modes at 1560 and 780nm and the TM_{01} mode at 780nm are shown. Calculations indicate that the better spatial overlap between the TM_{01} 780nm pump and TM_{00} 1560nm signal modes, and the negligible overlap of the TM_{01} mode with the 'dead' surface layer increase the effective nonlinearity by 3–4 times compared to the case where only TM_{00} modes are interacting.

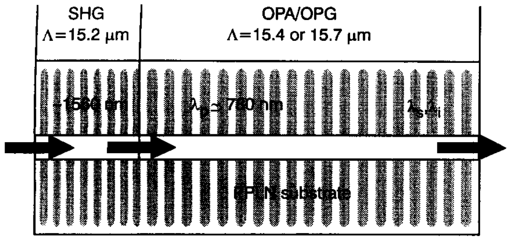

Fig. 1 *PPLN waveguide structure*

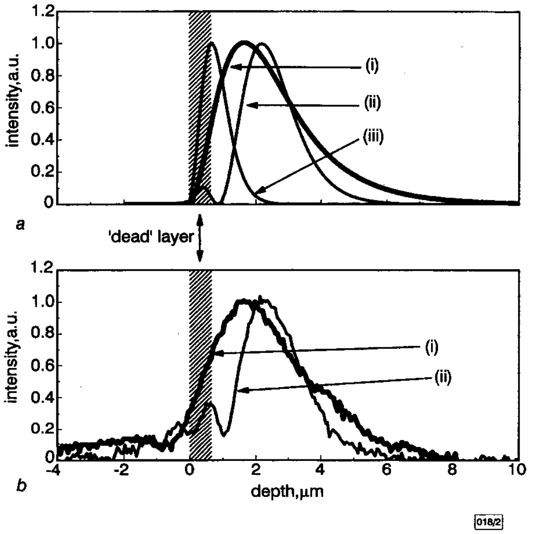

Fig. 2 *Calculated and measured depth profiles of interacting TM_{00} and TM_{01} modes at 1560 and 780nm*

a Calculated
(i) TM_{00} at 1560nm
(ii) TM_{01} at 780nm
(iii) TM_{00} at 780nm
b Measured
(i) 1560 nm
(ii) 780 nm

Testing of the OPA and OPG in the waveguides has been performed using a fibre laser, which provided 10–50ps pulses with wavelengths tunable from 1540 to 1570nm. Average powers of up to 200mW and pulse energies of up to 3.5nJ were available in this wavelength range. The pump and signal beams were combined externally to the waveguide structure using a dichroic coupler. The waveguides were typically kept at ~100°C to eliminate photorefractive effects.

The waveguide effective nonlinearities were inferred from the optical parametric generation (OPG) threshold measurements using eqn. 1. The OPG requires an optical gain of ~90dB. The majority of the waveguides, irrespective of their lengths, exhibited normalised effective nonlinearities η/L^2 in the range 80–150%/Wcm². This corresponds well with the theoretically expected nonlinearity of 100 – 120%/Wcm² for TM_{01} (780nm) to TM_{00} (1560nm) mode interaction as compared to the 30–40%/Wcm² expected for purely TM_{00} mode interaction. Measured depth profiles for 780 and 1560nm modes (Fig. 2*b*) are also consistent with the theoretically expected field distributions for TM_{01} and TM_{00} modes. The lowest OPG threshold corresponding to 7W of peak power for a 780nm pump was obtained in a 5cm long waveguide. Consequently, the effective nonlinearity of this device is 2000%/W. Pump-to-signal conversion efficiencies of ~35% were obtained for 780nm pump powers at 2–3 times the OPG threshold. We also have demonstrated that the wideband tunability of the signal and idler wavelengths is accessible by tuning the pump wavelengths from a fibre laser within only ~7nm (at 1560nm), as shown in Fig. 3 for two different QPM periods in the OPA section.

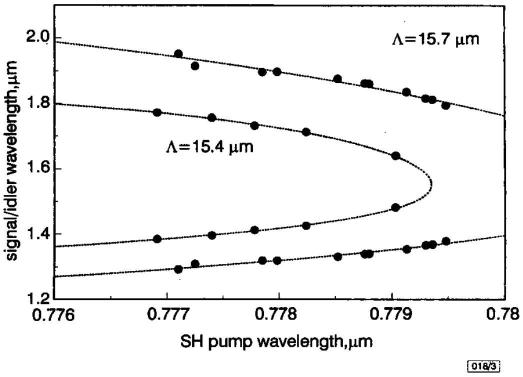

Fig. 3 *Wavelength tuning in waveguide OPG by tuning fibre laser wavelength*

For optical gain measurements we used CW seed signals from laser diodes at both 1480 and 1300nm. Experimentally measured gains of up to 65dB gain have been achieved with pump peak powers of ~ 10W. Some reduction of the gain compared to OPG measurements was obtained here due to residual mismatch between the OPA spectral band and the amplified signal wavelength. These experimental results indicate that amplification of 1–10GHz pulsed signals requires only 100mW to 1W of (pulsed) pump average-power in the waveguide. In a separate experiment, these waveguides were tested at average pump powers up to 1W. No significant problems were observed due to optical damage or the photorefractive effect. This demonstrates that practical OPA amplifiers can be fabricated and operated below optical and photorefractive damage thresholds with diode-pumped fibre-based pump sources.

In conclusion, we have demonstrated that highly nonlinear optical waveguides in PPLN can provide high gains at low pump powers available from fibre lasers and amplifiers. High conversion efficiencies and optical gains up to 90dB were achieved. Such amplifiers can significantly increase the bandwidth accessible for WDM optical communication systems. After further optimisation, high gains with CW pump powers of < 1W are anticipated. Additional advantages of OPA include unidirectional operation as well as the possibility of incorporating complex wavelength-switching functions [4].

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Fabrication of frequency spectrum synthesiser consisting of arrayed-waveguide grating pair and thermo-optic amplitude and phase controllers

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The fabrication is reported of an integrated-optic frequency spectrum synthesiser which is capable of shaping and encoding modelocked optical pulse waveforms by controlling the amplitude and phase of each line spectral component. The synthesiser consists of an arrayed-waveguide grating (AWG) pair for demultiplexing and multiplexing the spectral components and thermo-optic switches and phase shifters for arbitrarily patterning them. The dynamic range of the synthesiser is ~30dB and the amplitude and phase resolutions are 0.1–0.2dB and π/100, respectively.

Introduction: The shaping and encoding of optical pulse waveforms are very important processes for a variety of applications in optical communications, optical radar and picosecond and femtosecond spectroscopy. Control of the pulse temporal profile is achieved by spatially dispersing the optical frequency components, the amplitude and phase of which are arbitrarily weighted, and multiplexing them again into a single optical beam. Weiner *et al.* [1] first demonstrated a technique for optical pulse shaping using a grating pair as a dispersive element and masks for amplitude and phase filtering. Since they used a grating pair, the size of the experimental apparatus was of the order of $1\,m^2$. Also the weighting function of the amplitude and phase masks were fixed because they fabricated them by metal deposition and reactive-ion etching of the silica glass.

In this Letter, we describe the fabrication of a fully integrated frequency spectrum synthesiser for use in temporal pulse shaping. It utilises an AWG pair as a dispersive element and thermo-optic switches and phase shifters for spatial filtering. The device size is quite compact with a size of 9.2cm × 6.6cm and the weighting function of the spatial filter can be arbitrarily changed.

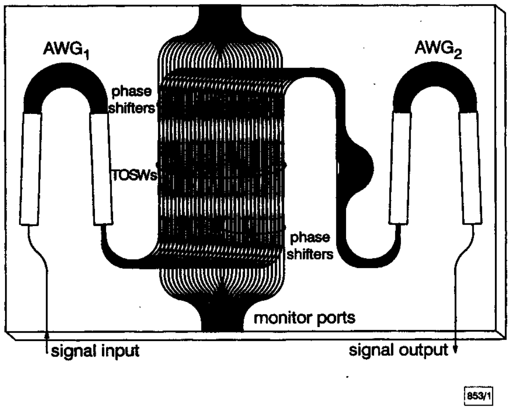

Fig. 1 *Schematic configuration of frequency spectrum synthesiser*

Experiment: The schematic configuration of the fabricated frequency spectrum synthesiser (FSS) is shown in Fig. 1. It consists of an AWG pair for demultiplexing (AWG$_1$) and multiplexing (AWG$_2$) the spectral components of modelocked optical pulses and thermo-optic switches (TOSWs) and phase shifters for arbitrarily patterning the spectral components. The channel spacing and the total number of channels of the AWG are 40 and 80GHz, respectively, which are centred at λ_0 = 1.55μm [2]. The centre wavelength mismatch between AWG$_1$ and AWG$_2$ is < 5GHz. 32ch of the 80ch of the AWG are used for spatial spectral filtering. An array of 32 TO switches and phase shifters is allocated between the AWG pair. All of the optical path lengths from AWG$_1$ to AWG$_2$ are made equal by employing path adjustment waveguides. The switching ratio of each TO switch, which can be controlled essentially from 0 to 1, is measured by using the monitor port. Also, the degree of phase shift in each path is determined by comparing the relative phase difference with the reference arm, which is not shown in Fig. 1. Fig. 2 shows the intensity transmission characteristics of the frequency spectrum synthesiser for the two extreme cases: all switches open and all switches closed. The fibre-to-fibre insertion loss is 12dB and the extinction ratio is ~30dB. Then, the dynamic range of the FSS is ~30dB. The average electric power for the TO switch is ~300mW. The minimum controllability of the electric power is 1 – 2mW. This enables us to obtain 0.1 – 0.2dB amplitude resolution. The average electric power necessary for obtaining π phase shift is also ~300mW. According to the previous minimum controllability of electric power, the resolution of the phase shifter is ~π/100.

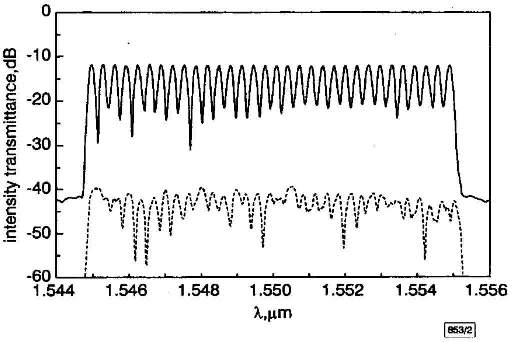

Fig. 2 *Intensity transmission characteristics of frequency spectrum synthesiser*

——— all switches open
– – – – all switches closed

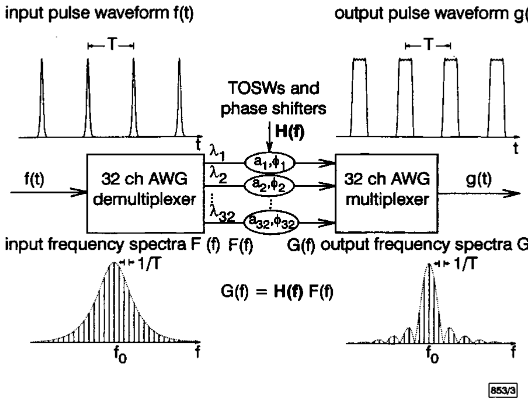

Fig. 3 *Schematic pulse waveforms and frequency spectra in square pulse generation scheme*

The frequency spectrum synthesiser can be used in a variety of applications for optical pulse multiplexing, pulse waveform shaping, frequency chirping compensation and frequency-encoding code division multiplexing (FE-CDM) etc. N times optical pulse multiplication can easily be realised by filtering the line spectral components of the modelocked pulse in every N intervals [3]. The square shaped optical pulse is a particularly useful pulse shape with potential application to nonlinear-optical metrology, coherent transient spectroscopy and future all-optical switching and optical demultiplexing [4, 5]. The frequency spectrum of a modelocked pulse train with the waveform $f(t) = A\,\mathrm{sech}(t/t_0)$ is given by

$$F(f) = \sum_{m=-\infty}^{\infty} A\,\mathrm{sech}[\pi^2 t_0 (f - f_0)]\,\delta\Big(f - f_0 - \frac{m}{T}\Big) \quad (1)$$