according to a Bernoulli process. The destinations of the arriving packets are random, with equal probability \(1/N\), and independent of each other. Fig. 2 shows parameter \(T\) (normalised to the packet duration time) for \(N = 16\) as a function of \(\lambda\), as attained by an ISB switching fabric with the proposed neural network (curve (i)), without the neural network (curve (ii)), and as attained by the ideal ISB switch [2] (curve (iii)). The figure highlights that the use of the neural network consistently increases the performance and enables nearly optimal performances to be obtained [2].

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References

30 ps chromatic dispersion compensation of 400 fs pulses at 10 Gbits/s in optical fibres using an all fibre photoinduced chirped reflection grating

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Indexing terms: Optical dispersion, Optical fibres, High-speed optical techniques, Gratings in fibres

Pulse recompression and dispersion compensation are demonstrated using 4 mm long all fibre photoinduced chirped reflection gratings at 1560 nm. Optical pulses of 400 fs at 10 Gbits/s are almost fully recompressed after undergoing broadening of \(\sim 30\) ps in an optical fibre; a compression ratio of 67 is achieved.

Introduction: Dispersion compensation and pulse compression is important in many areas of telecommunication, pulse amplification and ultrashort-pulse generation. The transmission span between regeneration in high bit rate optical fibre transmission systems is often limited by the effects of linear dispersion. A number of schemes have been proposed to compensate for dispersion [1, 2]. One proposed technique uses compact all-fibre chirped reflection gratings [2]. Chirped reflection gratings have the property of reflecting different wavelengths at different points along the grating length. If an optical pulse is launched into a chirped grating, then the spectral components of the pulse will be reflected with relative delays equal to twice the time of propagation to the point of reflection within the grating. The delay through a chirped grating has recently been measured [3]. Ideal chromatic dispersion compensation can be achieved in linearly chirped gratings if the reflected wavelength increases (or decreases) linearly along the grating length.

We have recently demonstrated a technique for fabricating photo-induced chirped fibre reflection gratings at any required wavelength and reported bandwidths of between 5 and 15 mm for 8 mm long gratings [4]. This Letter reports the application of such all-fibre chirped gratings for the first time in subpicosecond pulse recompression and dispersion compensation at 10 Gbits/s.

Fig. 1 Simulation results
(i) Neurons: (1, 3), (2, 1), (3, 4), (4, 2)
(ii) Neurons: (1, 4), (2, 2), (2, 3), (3, 1), (4, 1)

Simulation results and performance evaluation: We have considered the following typical switching problem. Suppose that in a given time slot, the matrix \(L\) for a \(4 \times 4\) switch is

\[
L = \begin{bmatrix}
0 & 0 & 1 & 1 \\
1 & 1 & 1 & 0 \\
1 & 0 & 0 & 1 \\
1 & 1 & 0 & 0
\end{bmatrix}
\]

We simulated the neural network (eqn. 1), with the parameters \(A = 2, B = 3, C = 1\), chosen in accordance with theorem 1, by using a standard fourth-order Runge-Kutta algorithm for solving eqn. 1 (see Fig. 1). The initial conditions, which constitute the neural network input data, were chosen so that the initial neuron output configuration \(V(0)\) coincides with the matrix of inputs \(L\). It is seen that once the transient motion is terminated, the neural network equilibrium coincides with the following output matrix:

\[
\beta = \begin{bmatrix}
0 & 0 & 1 & 0 \\
1 & 0 & 0 & 0 \\
0 & 0 & 0 & 1 \\
0 & 1 & 0 & 0
\end{bmatrix}
\]

As expected, the matrix \(\beta\) thus obtained represents the desired permutation matrix describing the optimal decisions for switching packets from inputs to outputs.

Fig. 2 Mean switching delay comparison

In deriving the performance of the switching fabric under consideration in terms of mean switching delay \(T\), we have assumed that packets arrive at each input port with a fixed probability \(\lambda\).

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Chromatic dispersion of calculated length dependence of the pulse width for a fibre with a pulse width goes through a minimum of -450 fs at a distance of -320 m long. The launched power was low so this weak background signal was launched into standard telecom-munications fibre -320 m long. The output pulse autocorrelation trace and spectrum are shown in Fig. 3. A solid line (also shown in Fig. 2) is the calculated length dependence of the pulse width for a fibre with a chromatic dispersion of 17.5 ps/nm-km. It can be clearly seen that the pulse width goes through a minimum of -450 fs at a distance of 245 m from the grating. This length corresponds to a dispersion of 0.35 ps/nm-km and the bandwidth is shown in Fig. 2. A solid line (also shown in Fig. 2) is the theoretical calculation of pulse width.

The 108 GHz train of 400 fs pulses was generated by a laser source based on a dual-frequency beat conversion technique [6]. The source generated optical soliton pulses (hence transform limited) within the grating bandwidth at 1560 nm. After reflection from the chirped grating the 400 fs pulses broadened to such an extent that they appeared as only a very weak background signal. This weak background signal was launched into standard telecommunications fibre -520 m long. The launched power was low so nonlinear effects were negligible. The fibre was then cut back a few metres at a time and the output measured by autocorrelation. The measured dependence of the pulse duration on the fibre length is shown in Fig. 2. A solid line (also shown in Fig. 2) is the theoretical calculation of pulse width.

Discussion: The experimental results clearly indicate that the grating has a dispersion almost identical to that of the 245 m length of fibre (calculated to be -26.8 ps/nm). The measured dispersion $D$ of the grating is 4.3 ps/nm, which is close to the theoretically predicted value of 5.1 ps/nm as estimated from $D = 2L/\Delta\lambda_f$.

where $V_f$ is the group velocity of the pulse in the fibre and $\Delta\lambda$ is the bandwidth of the grating. The input pulses of 400 fs were first broadened to ~30 ps and then recompressed to ~450 fs. The figure of merit $M$ which indicates the effectiveness of the compression can be defined as $M = \tau_i/\tau_r$.

where $\tau_i$ is the impulse width and $\tau_r$ is the pulse width after dispersion and recompression. The figure of merit was as high as 0.89 in these experiments, with a recompression ratio of ~60. Pulse compression of femtosecond pulses is most demanding [7], because the bandwidth is so large, and this has been shown to be possible. This demonstration shows that dispersion compensation in the femtosecond regime at hundreds of gigabits per second can be achieved effectively using simply produced chirped gratings. In the current demonstration, a loss penalty of 8.5 dB was incurred. Of this, 6 dB is due to the coupler, while another 2.5 dB due to the 75% reflection. However, the coupler may be replaced by an optical circulator to reduce the loss or other techniques employed to eliminate the 6 dB loss penalty. Gratings of near 100% reflectivity can also be fabricated, so that low loss all-fibre plug-in devices should be possible in the near future.

It should be noted that pulses can be dispersed in the same chirped gratings by propagating in the opposite direction having a reversed sign of dispersion, so that these gratings may find application in pre-chirped pulse amplification in-fibre without nonlinear effects followed by recompression.

Conclusions: It has been demonstrated for the first time that chirped all-fibre Bragg gratings may be used to compensate for linear dispersion of 400 fs femtosecond pulses in optical fibres at multi-gigabit transmission rates. A figure of merit of 0.89 has been achieved with near perfect recompression, at a compression ratio of 60 using simply replicated gratings. These results should prove encouraging for ultra-high-speed linear medium-to-long-haul systems.

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More intense than the other. In that spatial solitons recently reported [8] that if the beam widths are allowed to vary, attract each other if they are in phase, repel if they are out of phase [4], results on the interaction of two beams with different frequencies have also been reported [5, 6], but only in the limit where one beam is much more intense than the other. In that case, the weak beam essentially propagates in the index channel created by the strong beam through the third-order nonlinear refractive index, whereas the influence of the weak beam on the strong one can be neglected.

More recently, de la Fuente and co-workers [7] have shown theoretically that it is possible to have soliton 'pairing' in which beams of two different frequencies, but identical beam widths, can propagate together in the form of a single spatial soliton. We have recently reported [8] that if the beam widths are allowed to vary, although stationary solutions are not possible, interactions occur which give rise to fascinating and potentially useful phenomena including beamsplitting, switching and steering with all-optical control over the deflection angle. In this Letter, we show that some of these interactions can be used to produce an all-optical switch.

The switch: The goal of our work is illustrated schematically in Fig. 1, which shows two signal beams with different frequencies being injected into a Kerr-law medium. In Fig. 1a, the beams pass through each other so that output port 4 detects the signal at wavelength \( \lambda_1 \) and port 3 detects the signal at \( \lambda_2 \). In Fig. 1b, the two beams collide 'elastically' so that the wavelengths reaching the two output ports have been interchanged. The question is how to optically switch between these two states.

In this Letter, we consider beams with parallel polarisations. If, as an example, we choose \( \lambda_1 = 1.56 \mu m \) and \( \lambda_2 = 1.31 \mu m \) and \( P_1 < 0.5 P_2 \) (where \( P_1, P_2 \) are the powers of the two beams), the beams tunnel through each other, corresponding to the situation in Fig. 1a. This is illustrated using BPM simulations in Fig. 2, which also shows that the beams undergo a small spatial shift. The switched state shown in Fig. 1b can be achieved by changing the power and wavelength of signal beam 2. For example, we have observed that if \( \lambda_1 = 0.81 \mu m \) and \( P_1 > 0.5 P_2 \), then, rather than passing through each other, we obtain complete mutual deflection in which the two beams simply bounce off each other as illustrated schematically in Fig. 1b.

Of course changing the power and frequency of one of the signals so dramatically is not a very practical procedure. What these results suggest, however, is that we can achieve the required switching from the configuration in Fig. 1a to that in Fig. 1b by injecting a third (control) beam with the appropriate frequency and power.

In the case of three beams of different frequencies (which do not satisfy phase matching conditions), the wave equations governing the (scaled) electric fields \( \psi_1, \psi_2 \) and \( \psi_3 \) have the form

\[
2i k_1 \frac{\partial \psi_1}{\partial z} + \frac{\partial^2 \psi_1}{\partial x^2} + \left( |\psi_1|^2 + \frac{n_{12}}{n_{13}} |\psi_2|^2 + \frac{n_{13}}{n_{12}} |\psi_3|^2 \right) \psi_1 = 0
\]

\[
2i k_2 \frac{\partial \psi_2}{\partial z} + \frac{\partial^2 \psi_2}{\partial x^2} + \left( \frac{n_{12}}{n_{13}} |\psi_1|^2 + |\psi_2|^2 + \frac{n_{13}}{n_{12}} |\psi_3|^2 \right) \psi_2 = 0
\]

\[
2i k_3 \frac{\partial \psi_3}{\partial z} + \frac{\partial^2 \psi_3}{\partial x^2} + \left( \frac{n_{13}}{n_{12}} |\psi_1|^2 + \frac{n_{12}}{n_{13}} |\psi_2|^2 + |\psi_3|^2 \right) \psi_3 = 0
\]

where \( n \) is the linear refractive index, \( k_1, k_2, k_3 \) are wavenumbers, and \( n_{12} = k_{12}/k_1, n_{13} = k_{13}/k_1, \) and \( k_{12}, k_{13}, k_2, k_3 \) are parameters which depend on the particular nonlinearity mechanism and polarisation direction. Reduced equations for two frequencies have been given earlier [7].

For the parallel polarisations discussed here, \( k_1 = 2 \) and Fig. 2 corresponds to the situation where \( \psi_3 = 0, \lambda_1 = 1.56 \mu m, \psi_2 = 1.908 \) and \( P_1 = 0.4 P_2 \). If we inject a control beam \( \psi_3 \) into this system such that \( P_3 > 0.5 P_2 \) and \( n_{13} = 2.236 (k_3 = 0.7 \mu m) \), then we obtain the result shown in Fig. 3. The control beam deflects each of the signals so that, effectively, the two signal beams are reflected and the desired switch to the state described in Fig. 1b is achieved.

There is a slight change in position of the output beams on deflection (as shown in Fig. 3), but this can be adjusted by varying

\[
\begin{align*}
\lambda_1 & = \lambda_1 \\
\lambda_2 & = \lambda_2 \\
\lambda_3 & = \lambda_3 \\
\psi_1 & = \psi_1 \\
\psi_2 & = \psi_2 \\
\psi_3 & = \psi_3
\end{align*}
\]