The input power into the EDFAs located before and after the add/drop devices was −9dBm/channel and −7dBm/channel, respectively. The launched power into each fibre span was ~0dBm/channel.

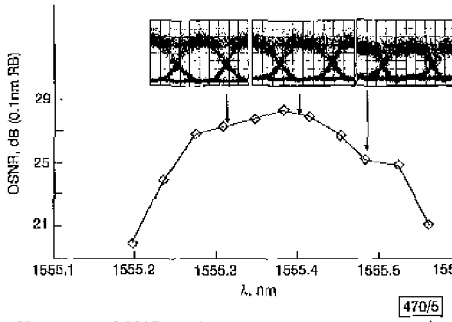

Fig. 5 *Change in OSNR and eye pattern against signal wavelength change after 16 cascaded nodes*

The net gain difference between channels after one loop was ~1dB, which results in 7dB of optical power variation among the channels at the receiver. The optical signal-to-noise ratio (OSNR) and Q value after 16 nodes were cascaded ranged from 24.5 to 29dB and from 17.5 to 20.5dB, respectively. Fig. 3 shows the BER after 16-node, 600km transmission. At 10^{-9} BER, the power penalty is < 1.5dB. The decision level of the receiver is optimised to remain error free at a signal OSNR of 25dB.

The above results were obtained by optimising the alignment between the filters and the channel wavelength. We then studied the sensitivity of the system by detuning the filters and channel wavelengths. Misalignment causes receiver sensitivity penalties caused by OSNR degradation and/or eye-distortion [5] from the filtering effects. Fig. 4 represents the received optical power penalty at BER 10^{-9} measured for channel 10 for a different number of cascaded nodes. When four nodes were cascaded, the 2dB power penalty bandwidth was > 0.4nm while it decreased to ~0.15nm after 16 nodes were cascaded. To investigate the main reason for the power penalty, we measured the changes in the OSNR and the eye pattern against wavelength detuning after 16 nodes were cascaded. The results are shown in Fig. 5. The eye patterns were measured at the optimum wavelength (1555.4nm) and with ±10GHz detuning from that wavelength. For the minimum misalignment between the signal and filter, the OSNR was ~28dB. With ±0.1nm detuning, the OSNR decreased to 25dB, which resulted from a 6dB decrease in the signal power and 3dB decrease in the accumulated amplified spontaneous emission (ASE) noise power density. Since the accumulated ASE noise was also filtered by the add/drop nodes cascade, the OSNR was less degraded due to the effect of detuning. The eye changes asymmetrically with detuning, which we attribute to the mixed effect of the filter phase response and the dispersion in the fibre. Based on the results of Fig. 5, the primary reason for the power penalty appears to be OSNR degradation for positive detuning and eye distortion for negative detuning.

Conclusions: Error free operation of 100GHz-spaced and 15 10Gbit/s/channel channel large scale (16 nodes cascaded over a total distance of 600km) optical network systems has been reported. The nodes are implemented using a wavelength interleaving filter and related multiplexer/demultiplexer. When 16 nodes were cascaded over 600km transmission, the OSNR ranges from 24.5 to 29dB and the BER penalty remains < 1.5dB. The available bandwidth with the receiver sensitivity penalty remaining < 2dB is ~0.15nm. The penalty is caused by OSNR degradation and eye distortion.

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Apodised fibre Bragg gratings fabricated with uniform phase mask using low cost apparatus

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New exposure schemes for fabricating apodised fibre Bragg gratings using a uniform phase mask are described. A sidelobe suppression level as high as 20dB in the lower wavelength region has been successfully achieved. The schemes allow the writing of truly apodised fibre Bragg gratings using low cost and simple apparatus.

Introduction: In dense wavelength division multiplexing (DWDM) communication systems, fibre Bragg gratings (FBGs) are good candidates for wavelength selection or filtering because of their low insertion loss, low polarisation dependent loss (PDL), low polarisation modal dispersion (PMD) and high wavelength selectivity. For passive devices in DWDM communication systems, sharp, well-defined filter amplitude responses are one of the most important characteristics [1]. For a typical FBG, the bandwidth is usually limited by the sidelobes in the spectral response [2]. A uniform FBG yields highly undesirable sidelobes due to Fabry-Perot resonance at the sharp boundaries of the grating. A well-discussed method for reducing these sidelobes is to apodise the grating coupling strength along the grating by gradually tapering the index modulation amplitude to zero at the two edges [3]. This helps to reduce the sidelobes in the higher wavelength, but it still leads to resonance which occurs at shorter wavelengths. In this way, the Bragg wavelength at either end of the grating is made smaller than that at the centre of the grating, and thus leads to larger sidelobes at lower wavelengths.

To further suppress these sidelobes, it is necessary to keep the average refractive index constant along the grating. Several approaches have been reported [4 – 6]. Pan *et al.* [4] used an apodised phase mask with variable diffraction efficiency to fabricate their steep skirt FBGs. Mola *et al.* [5] demonstrated a double exposure method by using shadow masks to control the index variation along the fibre. In contrast, Singh and Zippin [6] fabricated apodised fibre gratings by using a uniform phase mask and a single illumination process.

In this Letter, we propose new methods for fabricating apodised FBGs without using any intensity mask. FBGs with a uniform pitch are first photoimprinted by a UV beam with a Gaussian spatial profile using the standard phase mask approach. However, the average local refractive indices of the imprinted gratings are corrected to remain nearly constant along the whole length of the grating. We satisfy this requirement by using either a single exposure process or multiple exposure processes, both without requiring any intensity mask. Sidelobes at lower wavelengths have been significantly reduced to meet the requirements of DWDM communication systems.

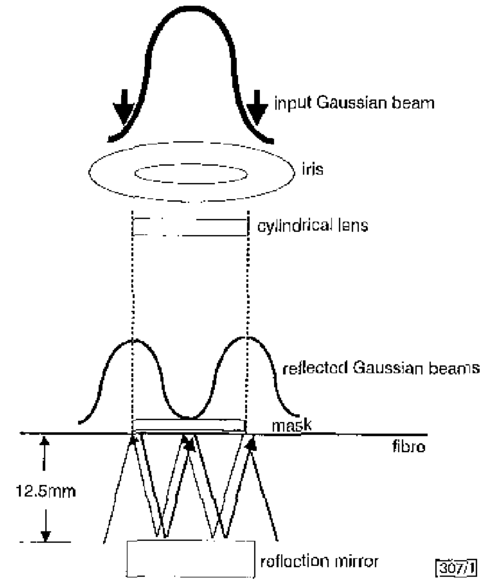

Fig. 1 Schematic diagram of fabrication of apodised fibre Bragg gratings by single exposure

Diagram not to scale

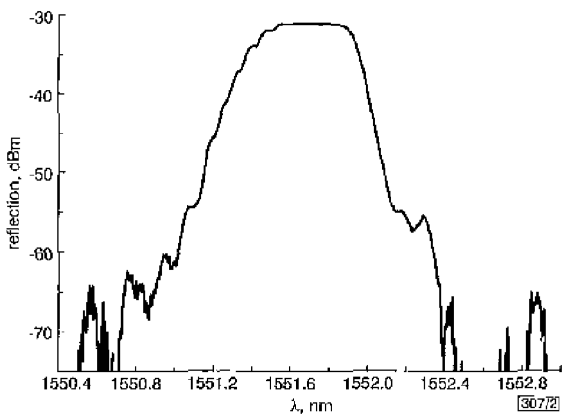

Fig. 2 Reflection spectrum of apodised fibre Bragg grating fabricated as in Fig. 1

Experimental setup and results: The basic principle of our schemes is to utilise the ±1 order diffraction beams produced by the phase mask to increase the average refractive index at both sides of the FBG. In our experiment, a Lamda Physik Compex 205 excimer laser was used to fabricate the FBGs. Since the beam profile of the laser intrinsically has a Gaussian distribution, the exposed FBGs are naturally formed with Gaussian apodisation without requiring additional optical components in the exposure apparatus. To perform better apodisation in a single exposure process, we placed a reflection mirror behind the fibre as shown in Fig. 1. An iris was set in front of the laser beam to control the exposure length. The photosensitive fibres used in this experiment were from Fibercore and had a numerical aperture of 0.12. The exposure length was set to 12mm, and the reflection mirror was placed 12.5mm away from the mask. The spatial profile of the reflection light from the mirror had a shape as shown in Fig. 1. The profile consisted of two offset Gaussian beams, which are ±1 order beams diffracted by the phase mask and then reflected by the mirror. Since the reflected lights travel a distance much longer than its coherence length, they do not lead to fringe formation, but only serve to increase the average index at both sides of the fibre grating. The reflection spectrum of a typical fibre grating fabricated by this method is shown in Fig. 2. The 3dB bandwidth is ~0.6nm and the sidelobes at both sides 100GHz from the centre wavelength are ~30dB smaller compared to the maximum reflectivity of the top band. This proves that the present scheme indeed can suppress sidelobes at lower wavelengths.

Another method for utilising the ±1 order diffraction beams for achieving a constant average refractive index is illustrated in Fig. 3. This is a multiple exposure scheme. After the standard photoimprinting exposure of the grating (3000 shots), we pull the phase mask away from the fibre by a distance of 25mm and perform the second exposure (4500 shots), with the iris adjusted to a width of 12mm. We then push the mask towards the fibre by a distance of 17mm, adjust the iris to a width of 6mm, and then perform the third exposure (3000 shots). The spectra of a typical FBG fabricated in this way are shown in Fig. 4. We find that the sidelobes at the lower wavelength 100GHz from the centre wavelength are suppressed by ~20dB, as shown in Fig. 4.

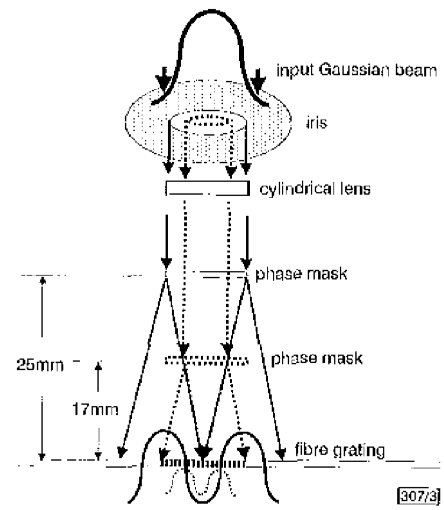

Fig. 3 Schematic diagram of fabrication of apodised fibre Bragg gratings by multiple exposures

- - - - first post-exposure
second post-exposure

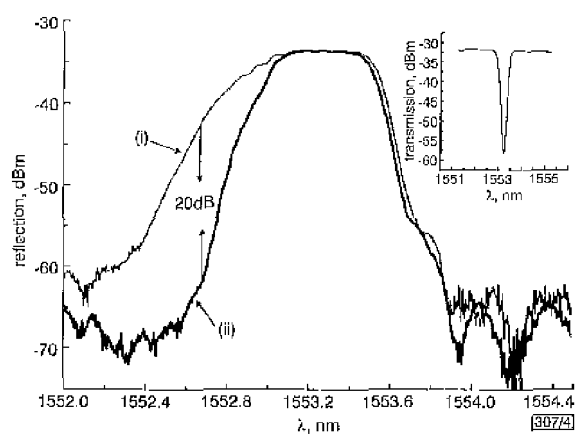

Fig. 4 Reflection spectra of raised Gaussian apodised grating fabricated as in Fig. 3

Inset: transmission spectrum
(i) Gaussian apodisation
(ii) raised Gaussian apodisation

Conclusions: We have developed two schemes that can be used to fabricate a raised Gaussian apodised FBG that has a constant average index variation, without requiring the use of intensity masks. Our methods can provide a flexible fabrication process and lead to a low cost and simple fabrication system. A sidelobe suppression of 20dB has been experimentally demonstrated. A higher suppression ratio could be achieved by carrying out more post-exposures. The performance of FBGs made by this method meet the requirements of DWDM communication systems.

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Planar lightwave circuit dispersion equaliser with reduced bias electrical power employing phase trimming technique

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A technique for reducing the bias electrical power needed for a chromatic dispersion equaliser on a planar lightwave circuit is presented. We applied a phase trimming technique to silica waveguides to reduce the operating power required for the equaliser. The results from preliminary trimming experiments, in which the equaliser was used to carry out second-order dispersion compensation are presented. The results show a successful reduction in the operating power.

Introduction: Techniques for compensating for fibre chromatic dispersion are becoming more and more important for advanced high bit rate optical communication and network systems. Several approaches to dispersion equalisation, such as the use of dispersion compensating fibres, chirped fibre Bragg grating dispersion compensators, and the mid-way spectral inversion technique, have been actively investigated with the aim of upgrading the capacity in installed fibre cables [1]. Of these approaches, compensating fibres are the most promising for practical dispersion compensation and are widely utilised. Planar lightwave circuit (PLC) dispersion equalisers, which we have developed and consist of several asymmetrical Mach-Zehnder interferometers (MZIs), have certain unique characteristics including compactness, dispersion variability, and the ability to provide dispersion slope compensation [2, 3]. Therefore, we expect PLC equalisers to be used for precise dispersion compensation in next generation higher bit rate (more than several tens of gigabytes per second) optical networks. In contrast, it is essential to control the waveguide phase in PLC equalisers by utilising the thermo-optic (TO) effect just to achieve fixed characteristics. As a result, we require a bias electrical power of as much as several watts to drive the equaliser [2, 3].

In this Letter, we describe a method for reducing the bias power in PLC equalisers. We have applied a stable phase trimming technique [4, 5], which was developed for a TO matrix switch consisting of symmetrical MZIs, to a silica-based lattice-form equaliser for the first time. This preliminary investigation consisted of a successful attempt to reduce the operating power in the equaliser and thus realised second-order dispersion compensation [6].

Experiments: Fig. 1 shows the configuration of the PLC dispersion equaliser we used in our experiments. The equaliser was composed of five asymmetrical MZIs cascaded in series. The relative index difference and the core size were 0.75% and 7.0 × 7.0μm², respectively. The arm length difference in the asymmetrical MZIs, ΔL, was set at 3.741 mm. The device was fabricated on a silica waveguide on Si by flame hydrolysis deposition and reactive ion etching [7]. A thin film heater was deposited on every arm to provide phase control for both trimming and the TO effect. We adopted fixed 3dB couplers in this configuration and the equaliser was capable of compensating for both normal and anomalous fibre dispersions with the same absolute value [6]. For example, the phase shift ϕ_i between the two arms in the asymmetrical interferometers must be set at or designed to be at $\pi/2$, 0, 0, 0, and $-\pi/2$ with a required centre wavelength for i = from 1 to 5, respectively, in order to achieve anomalous fibre dispersion compensation. Waveguide fabrication errors, however, cause the optical path length to deviate from these designed values. Therefore, we normally need to cancel out these deviations by using TO phase shifters. The typical total bias power can be as much as several watts. This power must be reduced for practical use.

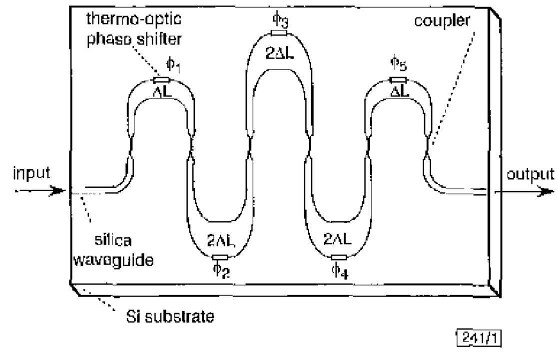

Fig. 1 *Configuration of PLC dispersion equaliser*
Δ = 0.75% and ΔL = 3.741 mm

We trimmed the waveguide phase errors using local heating [4, 5] to realise the anomalous fibre dispersion equaliser. The refractive index increased with time when we applied a much higher electrical power (5 – 8W) to the thin film heater than that in the normal TO phase shift (< ~1 W). This index change is considered to be due to the heating induced stress, which is described in detail in [5]. Figs. 2*a* and *b* show the measured loss and relative delay time characteristics of the PLC equaliser, respectively, before and after trimming. We carried out the trimming and measurement for the TE waveguide mode. We obtained the delay time characteristics by measuring the optical phase retardation at each frequency [8]. The normal dispersion value of ~450ps/nm was obtained over a frequency range of ~25GHz.

Table 1: Change of bias electrical power in PLC dispersion equaliser before and after phase trimming

Phase shifter	Power before trimming	Power after trimming
	W	W
ϕ_1	0.609	0.0
ϕ_2	0.500	0.0
ϕ_3	0.377	0.0
ϕ_4	0.075	0.0
ϕ_5	0.315	0.0
Total	1.876	0.0

Table 1 shows the change in the bias electrical power in each heater and in total before and after trimming. It is clear from this Table that the total power of 1.876W in all five asymmetrical MZIs was decreased to 0.0W by trimming. Phase trimming errors caused the slight deviation in the characteristics seen in Fig. 2.